DiFA Projects available for PhD cycle 40

Project code	**Main supervisor**	Title of the project
Baldi1	Baldi	Testing fundamental physics and cosmology beyond the standard model with numerical simulations of the cosmic large-scale structures
Bonafede1	Bonafede	Magnetic fields in protoclusters
Brusa1	Brusa	Unveiling Supermassive Black Hole winds at cosmic noon
Cadelano1	Cadelano	Constraining the primordial properties of dense stellar systems
Dallacasa1	Dallacasa	Development of techniques and tools to process radar signals for the observation of Near Earth Asteroids
Despali1	Despali	Galaxy evolution in alternative dark matter models
Despali2	Despali	A “SHARP” view of dark matter with strong gravitational lensing
Ferraro1	Ferraro	Searching for Fossil Fragments of the Galactic bulge formation process
Ferraro2	Ferraro	Playing with the physics of Blue Stragglers
Ferraro3	Ferraro	Probing the early history of the Milky Way formation with the chemical DNA of Bulge stellar systems
Ferraro4	Ferraro	Unveiling the physics of Globular cluster cores
Gitti1	Gitti	AGN feeding-feedback cycle in cool core clusters with Hα nebulae
Gitti2	Gitti	Radio and X-ray connections in cool core galaxy clusters
Lardo1	Lardo	A data-driven approach for Multiple Stellar Populations
Marulli1	Marulli	Cosmological exploitation of the statistical properties of Cosmic Voids
Marulli2	Marulli	Cosmology with Bayesian deep neural networks to learn the properties of the Cosmic Web
Marulli3	Marulli	Exploring Gravity Models with gravitational redshifts in galaxy cluster environments
Miglio1	Miglio, Straniero	Stars as laboratories for testing fundamental physics
Moresco1	Moresco	Exploiting Gravitational Waves as cosmological probes in view of the new upcoming large GW and galaxy surveys
Moresco2	Moresco	Cosmological constraints from the cross-correlation of Gravitational Waves and galaxy catalogs
Moresco3	Moresco	Towards a comprehensive clustering analysis: maximizing the scientific return through the combination of lower-order and higher-order correlation functions in configuration and Fourier space
Moscardini1	Moscardini	Statistical Tools for Cluster Cosmology Studies in the ESA-Euclid Era Mission
Moscardini2	Moscardini	A multi-wavelength view of galaxy clusters and AGN from Euclid and XMM-Newton
Moscardini3	Moscardini	Detection of galaxy clusters, peaks and cosmic voids in Weak Lensing Simulations: paving the way to the ESA-Euclid Mission data
Mucciarelli1	Mucciarelli	Near-Field Cosmology with Metal-Poor Stars
Mucciarelli2	Mucciarelli	Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies
Nipoti1	Nipoti	Hydrodynamic simulations of Terzan 5 and BFFs
Nipoti2	Nipoti	Global stability of stellar discs with dark matter halos
Nipoti3	Nipoti	Simulations of the collisional evolution of globular clusters with Monte Carlo methods
Nipoti4	Nipoti	Local gravitational instability of stratified rotating fluids

Project code	Main supervisor	Title of the project
Pallanca1	Pallanca	Exploring binary millisecond pulsars in globular clusters through optical/near-infrared observations.
Pozzi1	Pozzi	Illuminating the Dark Side of Cosmic Star Formation
Talia1	Talia	Exploiting the Euclid Legacy for galaxy evolution with ELSA
Vazza1	Vazza	Advanced simulations of the Radio Cosmic Web
Vignali1	Vignali	Tracing the Early Cluster Assembly with Accreting Black Holes in Enormous Lyα Nebulae at z=2–3
Vignali2	Vignali	The realm of dual super-massive black holes
Vignali3	Vignali	Shedding light on the physics of the most massive, highly accreting SMBHs at high redshift through a multi-wavelength study
Vignali4	Vignali	The realm of the high-redshift Universe unveiled by JWST

PhD project in ASTROPHYSICS

Title of the Project: *Testing fundamental physics and cosmology beyond the standard model with numerical simulations of the cosmic large-scale structures*
Supervisor: Prof. Marco Baldi

Scientific Case: The standard cosmological model (known as ΛCDM) has provided us with a surprisingly simple framework to describe and accommodate the vast majority of observational data. Nonetheless, recent **observational tensions** have led to **speculations about possible alternative and more fundamental explanations of cosmic acceleration.** Additionally, the lack of direct detections of Dark Matter calls for **a thorough scrutiny of many possible competing Dark Matter particle candidates**. In such a context, and with the advent of the epoch of so-called “Precision Cosmology”, **a detailed investigation of alternative cosmological models and of their impact on the formation and evolution of cosmic structures is essential** for a direct comparison between theory and observations. In this respect, **cosmological simulations play a crucial role**, opening a window on observable properties which cannot be predicted using analytical or simple linear numerical codes, including the statistical and structural properties of cosmic structures at highly nonlinear scales, and **their expected signal in a variety of observational channels** ranging from optical/near-infrared observations (Euclid/VRO), to radio observations (SKA), to gravitational wave surveys (Einstein Telescope).

Outline of the Project: The PhD student will work on **developing, optimising, and exploiting highly efficient and sophisticated numerical codes** to extend their capability of simulating a variety of extensions of the standard cosmological scenario, such as **Dark Energy models, Modified Gravity theories and non-standard Dark Matter candidates, and to extend these (Newtonian) algorithms to General Relativity**. More specifically, the PhD student will work on **the recently-developed PANDA code**, an extension to the state-of-the-art *Gadget4* code for cosmological N-body simulations.

The student will therefore work in the **highly stimulating and rapidly growing field of High-Performance Computing for Cosmology**, in collaboration with the recently established **National Centre for HPC**, developing the research plan described above for one (or more) of the following models:
- **Fundamental modifications of Gravity**: implementing and testing Horndeski Gravity models, K-mouflage models, Growing Neutrino Quintessence, General Relativistic Entropic Forces;
- **Effective modifications of gravity**: implementing and testing parameterised models of non-linear screening, Interacting Dark Energy, Clustering Dark Energy;
- **Non-standard Dark Matter**: extending the capabilities of existing N-body simulations codes including alternative Dark Matter candidates such as Ultra Light Axions or mixed Cold+Warm DM;
- **General Relativistic Simulations**: extending current Newtonian N-body simulations codes to include a fully relativistic treatment of gravity at large scales.

Although some of such models have already been implemented in simulations codes in the past, the technological and methodological advancements in the field of scientific High-Performance Computing witnessed in the last few years require a new design of most of these algorithms.
The choice of the specific models to consider will be discussed with the student and will be based on both the evolving priorities of the community and the student’s interests and attitudes.
More specifically, the student will:
- **Develop highly scalable and memory efficient modules** for one (or more) of the models listed above into the *Gadget4* (MPI/OpenMP, C++) simulations code, following the approach designed in the PANDA module;
- **Run large-scale and high-resolution simulations** for the selected model(s) and test the code performance for large production runs
- **Analyse the results of such simulations**, with a particular focus on the main observables that will be tested by upcoming large-scale surveys such as **Euclid, SKA, VRO-LSST, Einstein Telescope,** namely: **galaxy clustering**; **clusters and voids** properties; **weak lensing** statistics and cross correlation with clustering statistics; **CMB lensing** and Integrated Sachs-Wolfe effect; **Gravitational Waves** source distribution.

Contacts: Prof. Marco Baldi, marco.baldi5@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Magnetic fields in protoclusters

Supervisor : Annalisa Bonafede

Scientific Case:

Galaxy clusters are massive objects that form at the intersection of intergalactic filaments by accretion of lower mass groups and clusters. Most of the baryonic matter in clusters consists of a dilute hot thermal plasma, the intracluster medium (ICM) seen in X-rays, which permeates the cluster's volume. Radio observations have shown that the ICM is also filled with cosmic rays and magnetic fields, whose origin is still unknown.

In the ICM, magnetic fields play a crucial role in mediating particle acceleration mechanisms, AGN feedback, thermal conduction, and the ICM pressure and energy budget. For these reasons, obtaining constraints on the magnetic field and on its evolution has a deep impact on our understanding of ICM physics and dynamo processes, and it is one of the most important goals in cluster and plasma astrophysics.

Recent studies indicate that magnetic field in massive clusters at intermediate redshift ($z \sim 0.7$) are already amplified at the same strength as local clusters. This surprising result has challenged our understanding of magnetic field amplification throughout the cluster formation process.

At redshift larger than $z \sim 1$, most clusters are not the massive virialized haloes that we observe in the local Universe, but rather we see their progenitors, i.e. smaller gravitationally bound objects that will merge to make the final halo: the so-called **protoclusters.**

To understand the evolution of magnetic field in clusters, and trace their amplification, it is fundamental to have constraints on the magnetic field of the building blocks of local clusters.

Outline of the Project:

This Phd project aims at pushing our knowledge of magnetic fields to a new parameter space, by targeting clusters at the earliest stages of their formation. The PhD student will use new radio (JVLA and MeerKAT) data in polarisation on a sample of protoclusters to conduct the first investigation of magnetic fields at the epoch of cluster formation. A numerical code (MiRo') will be used to derive the magnetic field parameters from radio observations. The code can be further expanded to account for complex magnetic field models. Different leverage can be given to observational or numerical aspects, depending on the candidate attitudes and preferences.

The PhD candidate will be involved in international working groups, and travels to visit collaborators in Italy, Germany, and USA are planned.

Contacts: annalisa.bonafede@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title: *Unveiling Supermassive Black Hole winds at cosmic noon*

Supervisor: Marcella Brusa (DIFA; marcella.brusa3@unibo.it)

Co-Supervisors: Dr. Giorgio Lanzuisi (INAF-OAS, giorgio.lanzuisi@inaf.it),
Dr. Luca Zappacosta (INAF-OARoma, luca.zappacosta@inaf.it);
+ involvement in the WISSHFUL, SUBWAYS, and HYPERION collaborations

Scientific Case: AGN-driven multi-phase and multi-scale winds are thought to play a fundamental role in shaping the Super Massive Black Hole (SMBHs)/galaxy co-evolution by quenching the growth of both the SMBH and the stellar component and possibly explaining the tight SMBH-host mass relation. In particular, Ultra-fast Outflows (UFOs) — the fast (v_{out} > 10^4 km/s) and highly ionised thick winds launched in the inner regions (tens of gravitational Radii) of the SMBH accretion disk, and observable only in the X-rays through absorption features of He- and H-like iron at 6.67 − 6.97 keV — are thought to be the first engine powering the winds seen in other phases (atomic, ionized and molecular) at larger scales (see Fig, 1).
To be relevant for AGN/galaxy co-evolution, AGN feedback must have been in place when both BH growth and star-formation were at their peaks, i.e., $z \gtrsim 2-4$. Moreover, the incidence and power of UFOs are expected to be higher in luminous QSOs. Probing the frequency of UFOs and comparing their energetics with kpc-scale outflows in high-z, luminous QSOs is, therefore, key to understanding the impact of AGN-driven winds.

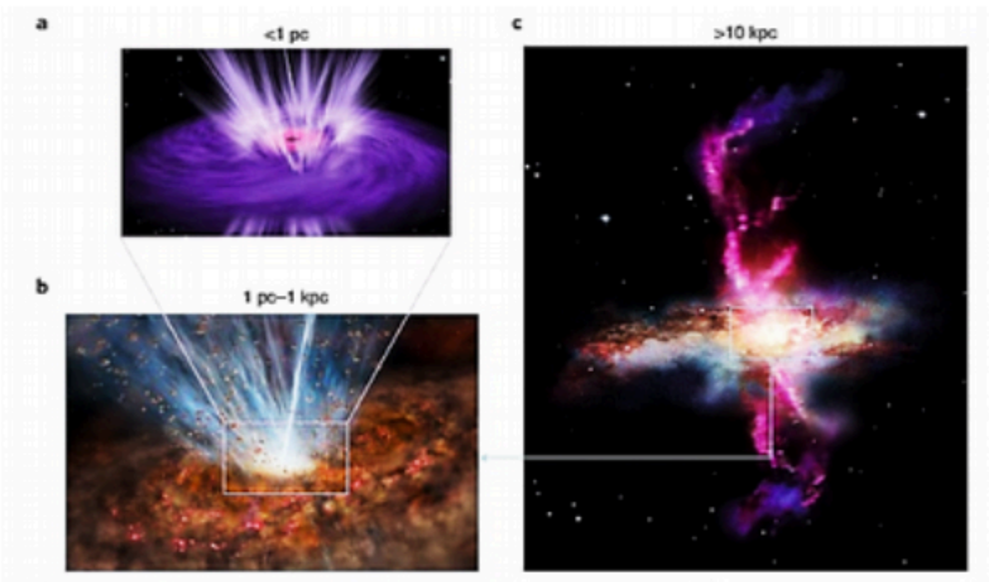


***Fig. 1:** Artistic view of multiphase AGN-driven winds highlighting the different phases and scales that are involved in the outflow. The wind originates as a UFO from the central engine (< 1 pc; a), it propagates through the surrounding ISM (1 pc–1 kpc; b), out to the boundaries of the host galaxy (> 10 kpc; c). WISSHFUL will investigate the outflow in its launching phase, when the gas is highly ionized, and the presence of fast moving material can be revealed in X-rays. (adapted from Cicone, Brusa et al. 2018, Nat. As. 2, 176)*

Outline of the Project:

The PhD project has these main goals:

i) derive for the first time the prevalence of absorption features associated with nuclear winds/UFOs such features in a large sample of QSO at cosmic noon;
ii) investigate the nuclear wind launching mechanism by exploring correlations between wind and accretion properties in a luminosity/accretion range almost unexplored so far;
iii) explore the connection between the presence of nuclear winds and other X-ray properties (photon index, high-energy cut-off, α_{OX}, etc.) or host galaxy and environmental properties (e.g. presence of companions etc.)

In order to achieve these goals, we will exploit the proprietary XMM-Newton data (~2.2Ms in total) secured through the **WISSHFUL** program (PI: G. Lanzuisi), which will observe a sample of 15 hyper-luminous (L_{bol}>10^{47} erg/s) quasars at z~2−4. This is a *multi-year Heritage program* that will last for three years, starting May 2024. The PhD candidate will also have the possibility to work on already existing data from:

- the **SUBWAYS** project (PI: M. Brusa), devoted to the search for UFOs in ~25 QSOs at lower redshift
- the **HYPERION** program (PI: L. Zappacosta), devoted to the characterization of ~15 z>6 QSOs.

All together these three XMM projects constitute an unprecedented effort, coordinated by the Italian AGN/X-ray community, to expand our understanding of the details of accretion/ejection in Quasars across cosmic time through high-quality X-ray spectral analysis.

The PhD candidate will be trained in analyzing and interpreting AGN X-ray (and UV) data from XMM-Newton observations, in AGN physics and demographics, and in handling multi-band data catalogs. They will also acquire scientific independence by, e.g., writing observing proposals and presenting the results of the work at international conferences.

The PhD candidate will join the AGN surveys group at DIFA and INAF-OAS, and will have the opportunity to visit renown research Institutes and Universities abroad through our collaboration networks. Generous research fundings are available for the entire PhD program.

Contacts: marcella.brusa3@unibo.it (office 4S6)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: "Constraining the primordial properties of dense stellar systems".

Supervisor: M. Cadelano (Bologna Univ.)
Co-Supervisors: E. Dalessandro (INAF-OAS), E. Vesperini (Indiana Univ.), J. J. Webb (Toronto Univ.)

Scientific Case:

Star formation at any cosmic epoch is characterized by the presence of clustered systems such as molecular clouds, massive young clusters, open and globular clusters. Connecting the origins and primordial properties of such systems to their present-day properties is paramount to make a step forward in our understating of star formation in the context of galaxy evolution and of the physical processes by which stars and star clusters are formed end evolved. However, such a connection is still poorly understood. For instance, one of the main properties of star-formation that any predictive theory must be able to replicate is the role of stellar multiplicity. In fact, it has been long known that binarity and, more in general, stellar multiplicity is a fundamental and inevitable outcome of any star forming system. Few topics in astronomy are able trigger such vigorous discussions as how many stars are born in binary, triple or multiple systems and their role in the evolution of the host stellar systems. Such a role is of critical importance, as stellar multiplicity influences most of the observable properties of any stellar system (e.g., chemical enrichment, mass-to-light ratio and so on…), from star clusters to galaxies. While significant efforts have been made to study multiple systems in a variety of different environments, no consensus has been reached regarding their formation rate and impact on the long-term evolution of their host systems. Consequently, the knowledge of the primordial fraction of multiple systems is an essential component of any study aimed at understanding the formation and evolution of any stellar systems.

Dense stellar aggregates, such as star clusters, are ideal targets for constraining critical properties of star formation. These systems are found in all types of galaxies, from dwarfs to ellipticals, are populated by many stars and are typically easy to observe. Indeed, the goal of this PhD project is to constrain the primordial properties of star clusters in the Local Group through the observation of their present-day properties, with a particular focus on the properties of multiple stellar systems. This, in turn, will provide the link between star clusters in the local Universe and their high-redshift counterpart and will clarify the role of multiple systems in the cluster long-term evolution. Indeed, the presence of multiple systems in star clusters provides an energy source able to drastically alter the evolution of the clusters. Moreover, the evolution of multiple systems in star clusters produces a large population of exotic objects such as millisecond pulsars, blue straggler stars and so on, which provide a benchmark for stellar evolution under extreme conditions. Finally, interactions among multiple systems trigger merging event visible through both electromagnetic and gravitational waves. Therefore, star clusters are expected to provide the ideal laboratory to test future gravitational waves detectors.

Outline of the Project:

By using the most up-to-date N-body and Monte Carlo simulations of star clusters, accounting for a broad range of different initial conditions (such as cluster's mass, size, primordial binary fraction, black hole retention fraction) and orbits, it has been recently found that it is possible to link a wealth of present-day properties of star clusters to the primordial ones. For instance, the measurements of the binary fraction across the whole cluster extension provide a proxy to the primordial one and allows to constrain the role of the environment in determine how many binaries are formed are survive the cluster long-term evolution. Indeed, the synergy between these cutting-edge simulations and observations is opening a new window in our understanding of the cluster star forming processes. In such a scenario, our group already awarded more than 150 hours of observations of different stellar systems with the most advanced ground-based and space facilities.

During the first year, the candidate will learn how to perform high-precision photometric analysis of stellar systems. This will provide the present-day distribution of single and multiple stars within the clusters and the physical properties of cluster themselves. Then, during the second year, the candidate will spend a period abroad, likely in the US and/or Canada, working with the most experts in the dynamical modelling of star cluster through numerical simulations. These simulations, combined with the results obtained from the observations, will provide the main goal of the PhD thesis, i.e., the derivation of the primordial properties of star clusters, which will be the focus of the third year of activity.

Contacts:

Mario.cadelano@unibo.it
Emanuele.dalessandro@inaf.it

PhD project in ASTROPHYSICS

Title of the Project: Development of techniques and tools to process radar signals for the observation of Near Earth Asteroids.

Supervisor :
Prof. Daniele Dallacasa, DIFA - Università di Bologna

Co-Supervisors :
Dr. Giuseppe Pupillo, INAF - Istituto di Radioastronomia
Dr. Simona Righini, INAF - Istituto di Radioastronomia

Scientific Case:
Radar experiments have been successfully used in the exploration of the Solar System, both from orbit and from ground. Radar echoes can be processed to achieve a variety of information on the target, such as astrometric measurements for orbital refinement, images for the characterization and the geological study of the surface and subsurface of Solar System bodies, etc.
Ground-based radars are frequently used to perform such experiments on Near Earth Objects (NEOs) with a detail that cannot be achieved using optical telescopes. The currently existing facilities for radar observations of NEOs are located in the United States; there are plans to develop such capability also in Europe, for both scientific and planetary defense aims.

Outline of the Project:
The candidate will learn the basics of radar signal processing techniques, developing and specialising them to the case of NEO observations, and testing them on past data available in public or proprietary archives. He/she will help in the definition of a European ground-based planetary radar system, through modelling of the performance and simulation of observations. He/she will also analyse data from currently-available observations performed using receiving facilities in Europe and help planning and executing future measurement campaigns using the antennas available in INAF, with the final goal to enable such observations to produce both astrometric and imaging results. The candidate will be responsible of the study and modelling of electromagnetic propagation, of the implementation of numerical simulations and methods for radar observations and radio signal analysis. He/she should possess at least basic skills in high-level programming languages (Matlab, Python, etc.).
These activities will be performed in collaboration with ESA, NASA/JPL and radar imaging experts at the University of Helsinki.

Contacts:
giuseppe.pupillo@inaf.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: **Galaxy evolution in alternative dark matter models**

Supervisor : Dr. Giulia Despali
Co-Supervisors : Prof. Lauro Moscardini

Contacts: giulia.despali@unibo.it

Scientific Case:

One of physics and astronomy's most pressing questions today is: *"**What is dark matter?**"*. Astrophysical studies have shown that the standard cold dark matter model (CDM) successfully reproduces observed structures in the Universe on large scales and the CDM. Still, tensions with observations persist at the scales of galaxies and below. A solution comes from alternative dark matter models (Warm or Self-interacting) that are able to influence the dark matter distribution at the centre of galaxies and satellites. The next generation of telescopes will bring exceptional progress in the observational domain, providing a much larger sample of lens systems (Euclid) and resolving scales down to milli-arcseconds (ALMA,

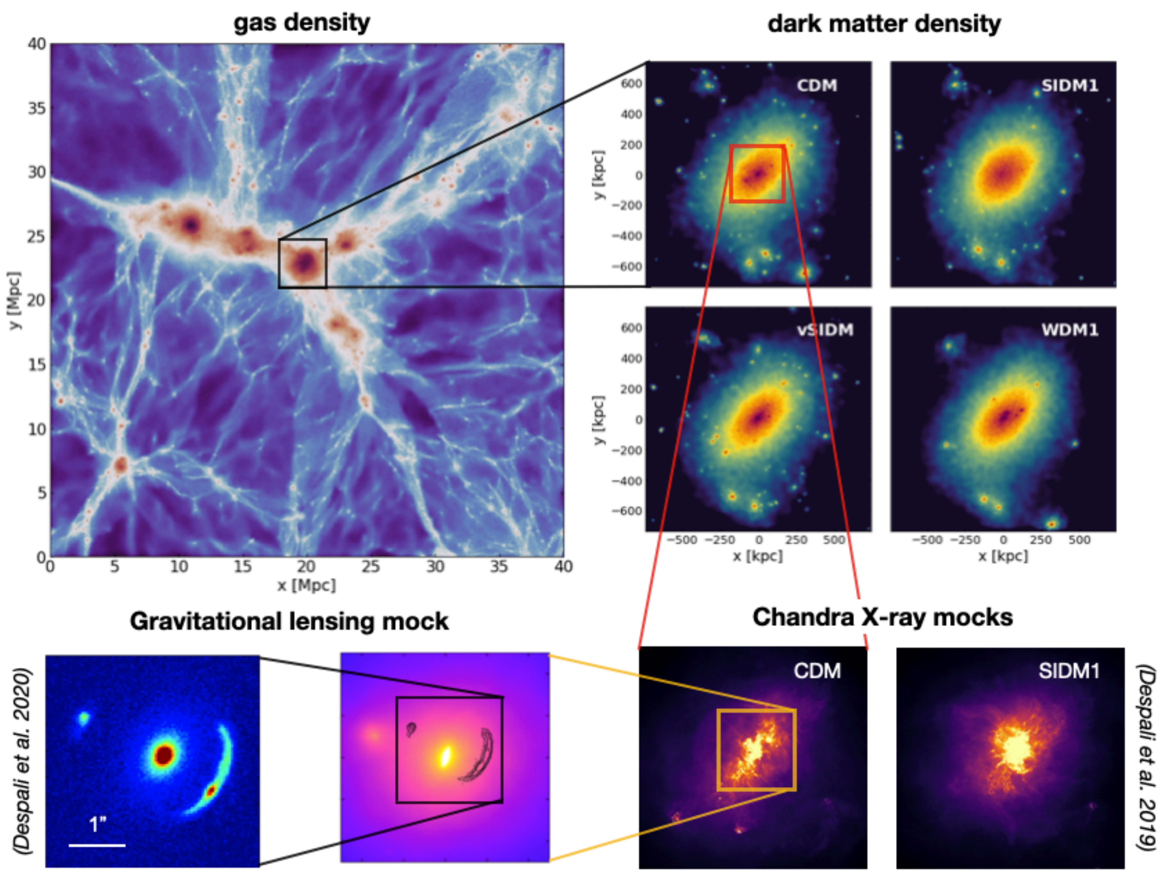


Figure 1. Visualisation of a the gas density in a cosmological volume from the AIDA runs. Then zooming to the smaller scales: the density of dark matter in a single halo in different dark matter models, the simulated X-ray emission in the Chandra 0.5-2 keV band and a realistic HST mock observation of strong gravitational lensing.

VLBI, ELT): **it is thus the moment to take theoretical predictions to the next level,** by modelling the effects of baryons and alternative dark matter at the same time.
The **AIDA simulations** are a new set of cosmological hydrodynamical simulations based on different dark matter models, including a realistic recipe for galaxy formation: they are the best simulations available to study the nature of dark matter from cosmological scales to dwarf galaxies. Thanks to the high resolution and complexity of the simulations, we will be able to systematically compare the properties of structures, from clusters to dwarf galaxies, and create mock observations in order to find estimators that can lead to new constraints and a better understanding of the physics of structure formation.

Outline of the Project:

Warm dark matter influences the number of low-mass galaxies and satellites, while self-interacting models modify the structural properties of dark matter haloes. This PhD project involves both creating part of the simulations with such models and analysing their output, thus learning the fundamentals of computational astrophysics. Breaking the conventional separation between theoretical and observational works, we will simultaneously learn about dark matter and galaxy formation models. In particular:

- The first phase of the project will consist of an analysis of the cosmological runs, identifying new statistical differences between CDM, WDM and SIDM. For example, scaling relations of galaxies, the number count of haloes and subhaloes, the matter power spectrum, and the evolution of the gas and stellar content of galaxies.
- In a second phase, the PhD student will then run additional boxes or identify systems to re-simulate at higher resolution, to create zoomed versions of a few interesteing galaxies. This will allow us to resolve the galaxy and dark matter structure with increased precision and create realistic mock observations to be compared with real observational data from Euclid and other telescopes (see Fig. 1 for examples of simulated observations).
- The results will be interpreted in the context of the current best data, such as the wide-field survey that will be carried out by the Euclid telescope. In this way, we will derive new constraints on the nature of dark matter.

The AIDA simulations are currently being developed in an international collaboration that includes DIFA and INAF scientists in Bologna, together wit the IllustrisTNG group: Volker Springel, Annalisa Pillepich, Dylan Nelson and Mark Vogelsberger. This will allow the PhD student to interact with some of the most prominent researchers in the field of numerical simulations. In addition, the student could be involved in the ESA Euclid consortium and the SHARP lensing collaboration, focused on constraining dark matter with lensing. The collaborations mentioned above will also provide the chance to spend a period of 3-6 months abroad.

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: A "SHARP" view of dark matter with strong gravitational lensing

Supervisor : Dr. Giulia Despali
Co-Supervisors : Prof. Lauro Moscardini, Dr. Cristiana Spingola (IRA)

Contacts: giulia.despali@unibo.it

Scientific Case:

In strong gravitational lensing, the image of a high-redshift source (e.g. a galaxy or a quasar) is distorted and magnified by the presence of an intervening object along the line-of-sight that acts as a lens (see Figure 1). Lensing is thus one of the most promising tools in dark matter studies: the distortion is due to gravity only, allowing one to directly measure the total (luminous and dark) mass distribution of the lens. Besides the main lens, strong lensing can detect low-mass satellites of the main galaxy. These are crucial tests of alternative dark matter: *(i)* their number is the fundamental test of cold and warm dark matter models; *(ii)* self-interacting dark matter can make low-mass structures very dense and thus more easily detectable with lensing.

In galaxy-galaxy lensing, dark subhaloes are detected as localised perturbations to the surface brightness distribution of magnified arcs. This method is, to this day, the only way to detect them beyond the Local Group and has led to detections in HST, Keck and ALMA data. It is easy to understand that the spatial resolution of the lensing images is crucial to detect small structures. The SHARP collaboration and observing program has targeted 40 new systems that have or will be observed soon with the Keck telescope: this is the only new optical sample that targets lensed arcs beyond HST resolution. This way, we can reach smaller scales and detect perturbers down to $M \sim 10^7$ $M_{\odot}$. The analysis of this dataset will provide new constraints on the number of dark subhaloes and the dark matter particle mass.

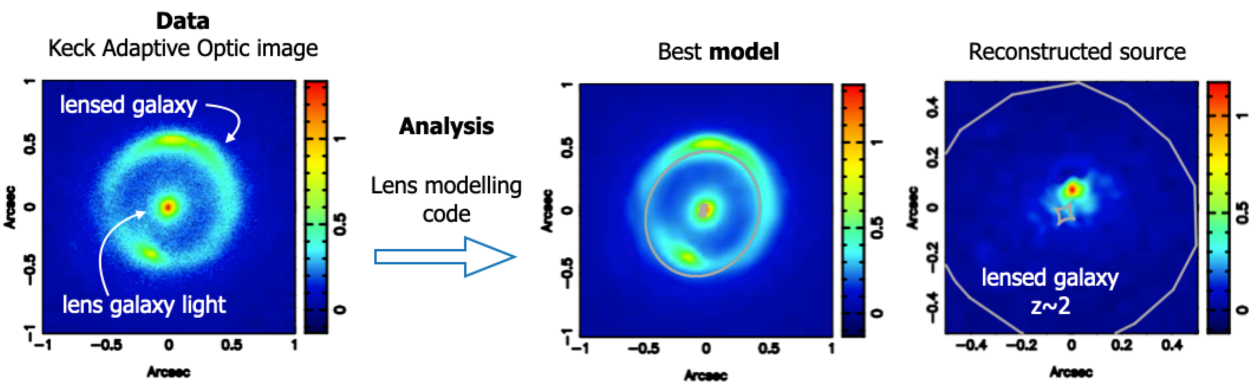


Figure 1. Example of the data analysis process of lens modelling: from the images reconstruct the mass and light distribution of the lens, as well as the surface brightness of the background source. Perturbations of the surface brighness of the arc would reveal the presence of dark substructures.

Outline of the Project:
The current SHARP sample consists of data from two observing runs with the adaptive optics system on Keck, including NIRC2 (H and K' bands) and Osiris. Thus, this program will bring gravitational imaging to the same level of constraints of MW-satellites and flux ratio anomalies and will make combined constraints stronger.

The PhD will focus on the analysis of lensing data from the SHARP sample and follow-up data, publishing the resulting models and the observational constraints. These will be interpreted thanks to the comparison with numerical simulations and mock observations.

In practice:

- The PhD student will model the new SHARP lenses, reconstructing the mass and light distribution of the lenses, arcs and sources using existing parallel codes. She/he will then search for smaller satellites, which manifest themselves as surface brightness perturbations.
- The results will be compared to theoretical predictions on the number and properties of substructures derived from the literature and the AIDA simulations sample. This is a new set of hydrodynamical cosmological simulations in different dark matter models that are currently being created. The PhD student will extend an existing code to create simulated observations (see Figure 2) with the same properties as the real lenses.

The SHARP collaboration and Euclid consortium framework will allow the PhD student to interact with the gravitational lensing community. In particular, the SHARP data analysis will be carried out in collaboration with the PI of the SHARP program prof. Christopher Fassnacht (California UC Davis), and international researchers in Germany and the Netherlands. These collaborations will also provide the chance to spend a period of 3-6 months abroad, visiting partner institutes in Germany or the USA.

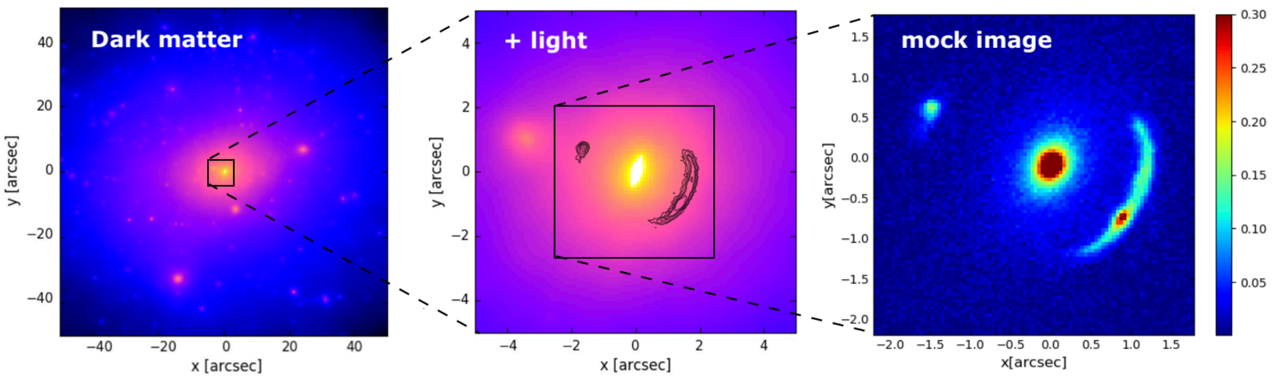


Figure 2. Examples of creating a mock observation from hydrodynamical simulations.

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Searching for Fossil Fragments of the Galactic bulge formation process

Supervisor: F.R. Ferraro **Co-supervisors:** B. Lanzoni, M. Cadelano **Collaborators:** E. Dalessandro (INAF)

Scientific Case: The scenario of galaxy bulge formation is still largely debated in the literature. Among the most credited models, the "merging picture" proposes that galaxy bulges form from the merging of primordial sub-structures, either galaxies embedded in a dark matter halo, or massive clumps generated by early disk fragmentation. Although the vast majority of the primordial fragments should dissolve to form the bulge, it is possible that a few of them survived the total disruption and are still present in the inner regions of the host galaxy, grossly appearing like massive globular clusters (GCs). At odds with genuine GCs, however, these fossil relics should have been massive enough to retain the iron-enriched ejecta of supernova (SN) explosions, and possibly experienced multiple bursts of star formation. As a consequence, they are expected to host **multi-iron and multi-age sub-populations**.
Two of these remnants (disguised as genuine GCs: Terzan5 and Liller1 have been recently discovered (Ferraro et al., 2009, Nature,462, 483) and Liller1 (Ferraro et al, 2021, Nat. Astr., 5, 311), in the bulge of the Galaxy. These systems (1) are indistinguishable from genuine GCs in their appearance, (2) have metallicity and abundance patterns incompatible with those of bulge GCs and well in agreement with those observed in the bulge field stars, (3) host a dominant old stellar population (testifying that they formed at an early epoch of the Galaxy assembly), (4) host at least one young stellar population, several Gyrs younger than the old one (demonstrating their capacity of triggering multiple events of star formation). It is important to emphasise that the multi-age components in both the BFFs identified so far were discovered by analysing proper motion (PM) selected color-magnitude-diagrams (CMDs) obtained by combining HST and AO-assisted ground-based IR images (acquired at ESO-VLT and Gemini; see Fig.2). Here we propose to secure deep second-epoch K_s Gemini images of 11 GC-like stellar systems into the Galactic Bulge to assess their stellar populations thus finally addressing their true nature. *The discovery of other BFFs would add new crucial information on the formation process(es) of the Bulge*

Outline of the Project: In this framework we are using high-resolution and NIR capabilities of GSAOI-GEMS at GEMINI, HST and JWST to secure multi-epoch observations of a sample of globular cluster-like stellar systems in the Galactic Bulge in order to search for other BFFs. 12 hours of observing time at GEMINI South telescope have been already allocated to this project.
With the final aim of providing the accurate characterization of the stellar populations in each of the investigated stellar systems, the student will be in charge of the construction of high-quality differential reddening corrected and Proper motion- selected color magnitude diagrams (CMDs). Proper motions will be obtained from the analysis of multi-epoch observations: in particular the new GEMINI data will provide second-epoch observations for a sample of 11 clusters already observed with HST. Moreover, the combination of near-IR and optical images will provide the appropriate characterization of the extinction law in the direction of each stellar system (Pallanca+19, ApJ,882, 159; Pallanca+21, ApJ, 917, 92). Note that an increasing number of studies is showing that the extinction law can significantly vary along different directions toward the Bulge (e.g., Popowski 2000,ApJ, 528, L9; Nataf+2013,ApJ, 769, 88). Indeed, the correct determination of the extinction law in the direction of each target is crucial, since it is the first, mandatory step for a proper correction of differential reddening, and a solid characterization of the evolutionary sequences in the CMD and it has direct impact on the determination of each stellar system distance.

Contacts: francesco.ferraro3@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

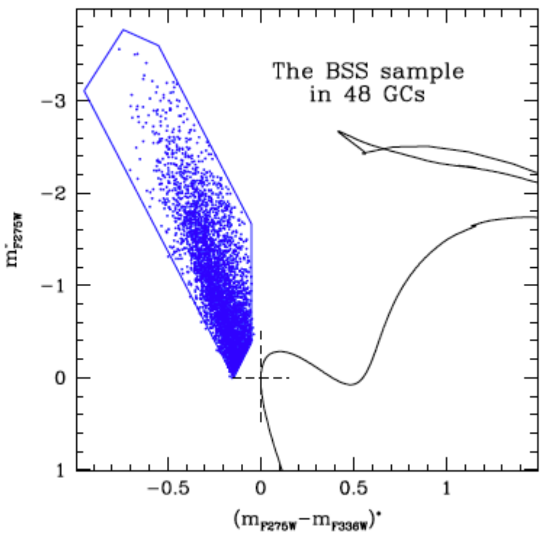
PhD project in ASTROPHYSICS

Title of the Project: *Playing with the physics of Blue Stragglers*

Supervisor: F.R.Ferraro **Co-supervisors:** B. Lanzoni, C. Pallanca, M. Cadelano

Scientific Case: GCs are among the most beautiful objects in the sky, but their importance goes far beyond their magnificent appearance. They are the best example of simple stellar populations and natural laboratories where properly testing the predictions of the stellar evolution theory. In addition, the large number of stars and the extremely high stellar densities in their center make GCs ideal laboratories to study the effects of dynamics on stellar evolution. In fact, from a dynamical point of view GCs are the only astrophysical systems that, within the time-scale of the age of the Universe, undergo nearly all the physical processes known in stellar dynamics, such as: gravothermal instability, violent relaxation, energy equipartition, 2-body and higher order collisions, binary formation and heating, etc. Hence GCs turn out to be key astrophysical laboratories for the simultaneous study of stellar evolution and stellar dynamics, two aspects that cannot be addressed independently: physical interactions between stars, as well as the formation and evolution of binary systems play a significant role in the overall evolution of the clusters and can considerably modify the observable properties of their stellar populations. Blue Straggler Stars (BSSs) are the most abundant product of this dynamical activity.

Outline of the Project: Being more massive than normal cluster stars, BSSs are thought to form either from mass-transfer processes in binary systems or by stellar mergers induced by direct collisions. They also are the brightest and most numerous massive stars in old clusters. Hence BSSs represent the best probe particles for tracing the dynamical history of stellar systems, but their nature and properties are still largely unexplored. By means of a large photometric and spectroscopic database collected by our group (see the Figure), we plan: (i) to measure the BSS physical parameters (i.e. mass, gravity, temperature) of the entire photometric sample comprising more than 4000 BSSs; (ii) to measure the rotation velocity of a sample of BSSs in different environments (clusters with different densities); (iii) to search for chemical signatures of their formation mechanism, thus eventually unveiling their true nature; and (iv) to determine their radial distribution over the entire cluster extension in a number of Galactic GCs with different properties (central density, concentration, mass, etc). Indeed the level of segregation of these stars has been found to be a powerful indicator of the level of dynamical evolution suffered by the parent cluster (thus defining the so-called "dynamical clock" see Ferraro et al, 2012, Nature, 492,393; Ferraro et al. 2018, ApJ, 860, 26; Lanzoni et al., 2016, 833, L29, Ferraro et al., 2019, Nature Astronomy, 3, 1149, Ferraro et al., 2023, ApJ, 950,145).



Contacts: francesco.ferraro3@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project*:* Probing the early history of the Milky Way formation with the chemical DNA of Bulge stellar systems

Supervisor: F.R. Ferraro **Co-supervisors:** B. Lanzoni, C. Pallanca, L. Chiappino **Collaborators:** L. Origlia (INAF), C. Fanelli

Scientific Case: While observations of the distant Universe show that bulges of spiral galaxies form through multiple mergers of massive clumps of gas and stars, and are subsequently enriched by accretion events, no direct evidence of these processes has been found so far in the Milky Way Bulge. Still, the Galactic Bulge is the sole spheroid where individual stars can be observed, allowing a unique exploration of the debris of those primordial clumps and accreted structures. Indeed, the discovery that Terzan5 (Ferraro et al., 2009, Nature,462, 483) and Liller1 (Ferraro et al, 2021, Nat. Astr., 5, 311), two Bulge systems with the appearance of globular clusters (GCs), host multi-age and multi-iron populations, and share the same "chemical DNA" of Bulge stars strongly suggest that they could be Bulge Fossil Fragments (BFFs), the remnants of the proto-Bulge formation process. Thus, a variety of relics tracing different phenomena are expected to populate the Bulge: BFFs, in-situ formed and externally-accreted GCs, and also nuclear star clusters of cannibalized structures. Each system could provide a piece of information about the Bulge formation and evolutionary history. The signatures of the different origins are imprinted in the kinematic, photometric, and chemical properties of these stellar systems, and can be read with different levels of accuracy.

Outline of the Project: In particular, the chemical tagging is a very powerful tool to unveil the true nature and origin of stellar systems, because specific abundance patterns provide authentic "chemical DNA tests" univocally tracing the enrichment process, hence the environment where the stellar population formed. In fact, the atmospheres of the stars that we observe today preserve memory of the chemical composition of the interstellar medium (ISM) from which they formed, and the chemical abundances of the ISM vary in time if more than one burst of star formation occurs, owing to the ejecta of each stellar generation. Thus, stars formed at different times and in environments with different star formation rates (SFRs) have different chemical compositions, and by analysing the chemistry of each stellar population one can univocally trace the enrichment process of the ISM. Different abundance patterns are expected depending on the stellar polluters, the enrichment timescale and the SFR, with a few specific abundance patterns being so distinctive that they can be used as "DNA tests" of the stellar population origin.
In this framework we are leading a Large Programme at the ESO-Very Large Telescope (VLT) which exploits the superb performances of the spectrograph operating in the near-IR CRIRES+ to perform an unprecedented chemical screening of a representative sample of Bulge stellar systems, with the aim to determine their chemical DNA and finally unveil their true origin. A total of 255 hours of observing time was assigned to this Large Programme (PI: Ferraro).

The student will be in charge of the spectroscopic analysis of the high-resolution CRIRES spectra to derive chemical abundances of several key elements. In particular, beyond the iron, the abundance of many iron-peak elements (like Zinc, Vanadium, etc) and alpha-elements (like Calcium, Silicon, Magnesium, Titanium) will be derived. These abundances will be used to construct powerful chemical DNA indicators as the 'classical" [α/Fe]–[Fe/H] diagram and to test the new-defined DNA test involving [V/Fe] and [Zn/Fe] ratios. The combination of these test will allow a solid distinction between in-situ formed and accreted GCs and the univocal identification of the environment in which the stellar systems formed.

Contacts: francesco.ferraro3@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Unveiling the physics of Globular cluster cores*

Supervisor : F.R. Ferraro **Co-supervisors:** B. Lanzoni, M. Cadelano, C. Pallanca

Scientific Case: The Universe we live in is dominated by darkness. Indeed, the vast majority of the matter (and possibly of the energy) in the Universe is dark, while only a few percent can be revealed through light signals. Fortunately the presence of dark matter (DM) leaves imprints in the kinematical properties of the luminous mass, revealing invisible structures as DM halos and super-massive black holes. This project is devoted to study the kinematics of sub-galactic stellar systems with the aim of unveiling and probing the existence of non-visible matter at the globular cluster (GC) scales. Finding DM halos in sub-galactic structures would be crucial to alleviate the cosmological "missing satellite problem". Identifying intermediate-mass (10^3-10^5 $M_\odot$) black holes (IMBHs) in GCs could shed new light on the formation processes of the SMBHs observed in galaxies and AGNs already at redshift $z>6$. Precisely determining the internal structure and kinematics of GCs would also fill our current lack of knowledge about the physics of these stellar systems, which are true astrophysical milestones.

Outline of the Project: To address these issues we propose to perform the most comprehensive study ever attempted to determine the internal structure and kinematics of GCs. Specifically, we propose to determine the projected density distribution, the velocity dispersion profile and the rotation curve, from the very center out to the tidal radius and through unbiased methodologies, for a sample of 36 Galactic GCs well representative of different structural parameters, dynamical stages and environmental conditions. The line-of-sight (LOS) kinematics will be determined from the spectra of several hundreds individual stars located along the entire extension of each GC, by exploiting state-of-the-art technology in a non-conventional way. The data needed to perform this part of the project are already acquired by means the ESO Multi-Instrument Kinematic Survey (MIKiS) that consists of 2 Large Programmes at the ESO-VLT (PI: Ferraro, for a total of 300 hours of observing time). We combine: *(i)* Adaptive Optics (AO) Integral Field Spectroscopy (IFS) in the innermost cluster regions (arcsecond scale), *(ii)* seeing-limited IFS for the intermediate radial range (tens of arcsecond scale), and *(iii)* wide-field multi-object spectroscopy for the most external regions (from one to tens arcminute scales).
A detailed presentation of the survey and first results can be found in: Ferraro et al., 2018, ApJ, 860, 50; Ferraro et al., The Messenger, 172, 18; Lanzoni et al., 2018 ApJ, 865,11; Lanzoni et al., 2018, 860, 95.

PROPER MOTIONS - Accurate proper motions (PMs) of individual stars in the center of each GC will be computed from multi-epoch HST images. This will provide us, for the first time, with the 3D kinematics of dozens of central stars, thus allowing us to reconstruct their orbits and recognize possible high-velocity objects accelerated by an IMBH. Moreover, we will properly sample the very central regions, where the most interesting dynamical processes are expected to occur (but where PMs of stars below the main sequence turnoff are not precisely measurable in most GCs because of crowding; see Watkins et al. 2015, ApJ 803, 29). This is crucial to detect possible central LOS velocity dispersion cusps. The PMs released by the GAIA space mission will complement this information in the external cluster regions, thus providing us with the 3D cluster kinematics along the entire radial extension.

Contacts: francesco.ferraro3@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

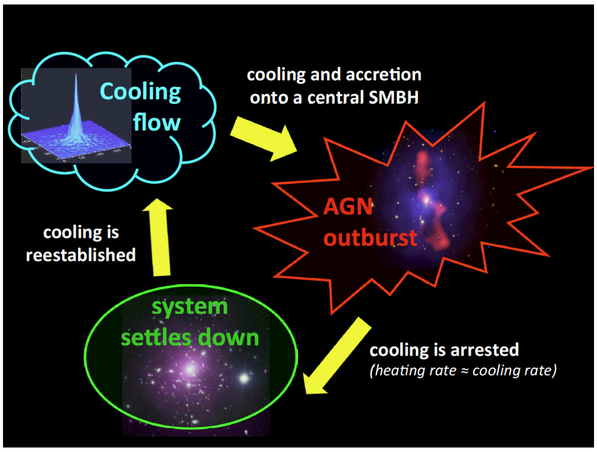
PhD project in ASTROPHYSICS

Title of the Project: *AGN feeding-feedback cycle in cool core clusters with Hα nebulae*

Supervisor : Myriam Gitti (DIFA)
Co-Supervisors : Fabrizio Brighenti (DIFA), Francesco Ubertosi (DIFA)

Scientific Case:

In the absence of a heating source, the intra-cluster medium (ICM) at the center of the so-called 'cool core' galaxy clusters should cool, condense, and accrete onto the brightest cluster galaxy (BCG) and form stars. The end products of cooling, as inferred e.g., from Hα nebulosity, are observed in many BCGs in the forms of cold molecular clouds and star formation, but in quantities at least an order of magnitude below those expected from uninterrupted cooling over the age of clusters (e.g., *Peterson & Fabian 2006, Phys. Rep., 427, 1*). The implication is that the central gas must experience some kind of heating to balance cooling. The most promising heating candidate has been identified as feedback from energy injection by the central active galactic nucleus (AGN), manifesting in highly disturbed X-ray morphologies (cavities, filaments, shocks and ripples) which often correlates with the morphology of radio jets and lobes (e.g., *McNamara & Nulsen 2007, ARA&A, 45, 117*; *Gitti et al. 2012, AdAst*).



This so-called 'radio-mode' feedback has a wide range of impacts, from the formation of galaxies to the regulation of cool cores, and can in principle explain why cooling and star formation proceed at a reduced rate. However, the details of how the feedback loop operates are still unclear.

Outline of the Project:

To clarify the regulation of the feeding and feedback cycle in cluster cores it is crucial to perform accurate studies of the cooling and heating processes for a sensible sample of clusters with a prominent cold ICM phase. We have identified a sample consisting of the X-ray brightest, most Hα luminous clusters visible from the Jansky Very Large Array (JVLA). In particular, we selected clusters from the ROSAT BCS sample with 0.1-2.4 keV flux f_X>7x10^{-11} erg cm^{-2} s^{-1} and Hα luminosity >10^{40} erg s^{-1}. Visibility from JVLA ensures that high resolution radio observations can be used to examine the interaction between radio-loud AGN, ICM and cooling gas. The sample includes some very well-studied systems (e.g., A1835, A1795, A2052), as well as clusters never observed in X-rays and/or with only snapshot radio data (e.g., A1668).

In the past years we obtained snapshot *Chandra* and new JVLA data for three clusters which lacked archival X-ray and radio data, and are now carrying out a follow-up campaign to acquire *Chandra* deep observations.

Our first results (see Figure) suggest that, in some systems with disturbed morphology, the cooling process is not currently depositing gas onto the BCG core (*Pasini et al. 2019, ApJ, 885, 111*; *Pasini et al. 2021, ApJ, 911, 66*; *Rosignoli et al. 2024, ApJ, 963, 8*).

The aim of the project is to investigate whether the feeding-feedback cycle of these strongly cooling clusters is broken, or if the AGN activation cycle is somehow maintained, for example being driven by the periodicity of the gas motions (sloshing). In particular, to determine the thermodynamical properties of the ICM and the morphology and spectral indices of the central radio sources, the PhD candidate will perform accurate morphological and spectral analyses of the *Chandra* and JVLA data already in hand, that will also be compared to the Hα nebulae from literature.

To obtain good-quality X-ray and radio coverage for the whole sample, the PhD candidate will propose for deeper *Chandra* and JVLA data of those clusters that only have snapshot observations, so as to be able to perform a thorough investigation of the range of cooling morphologies and interplay with the radio AGN in these clusters. They will also propose for complementary follow-up Atacama Large Millimetre Array (ALMA) CO observations to obtain detailed information on the distribution and kinematics of the molecular gas (as recently done in e.g., *Russell et al. 2019, MNRAS, 490, 3025*). Depending on the student interest, numerical simulations can further be developed to compare the observed data with detailed computational modeling tailored to the specific targets.
Comparing these with the X-ray and radio data will allow us, as the final goal of the project, to test key correlations between the different gas phases (plasma - warm - molecular), thus leveraging a multi-frequency approach to investigate the link between the hot ICM, optical filaments and molecular gas within cool cores, and to analyze in detail star formation in the BCG.

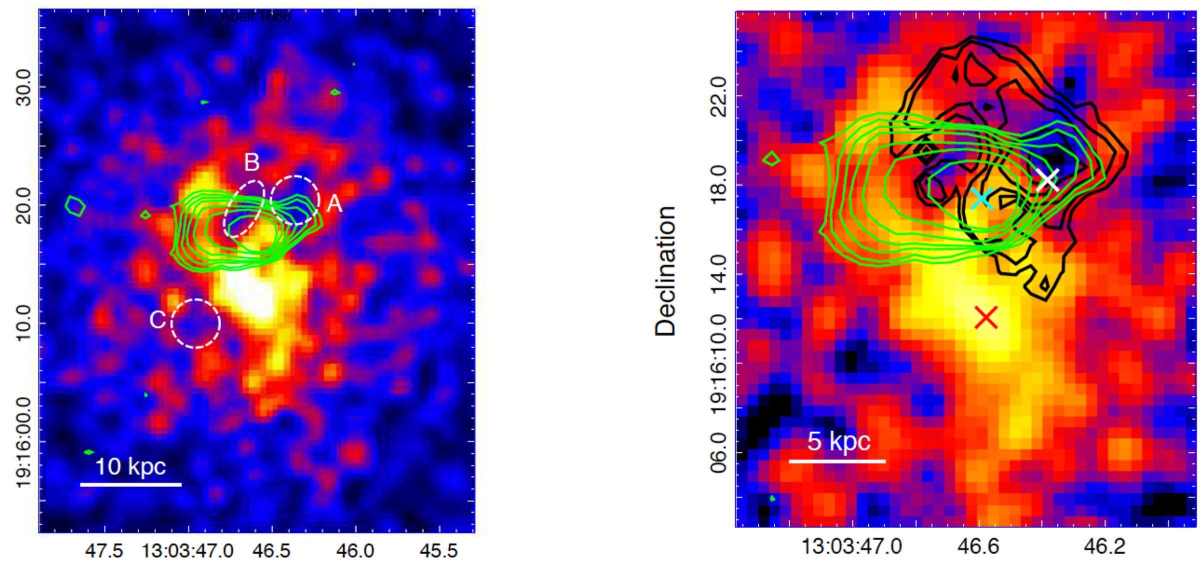


Figure - The results from our snapshot *Chandra* (color map) and 1.4 GHz JVLA observations (green contours) of A1668 indicate that this cluster has a disturbed morphology, showing hints of cavities (A, B and C in the left panel) and spatial offsets between the X-ray emission peak, the radio BCG and the Hα line emission (in the right panel, the cyan cross represents the X-ray emission centroid, coincident with the BCG center, the red and white crosses are the X-ray and Hα peaks, respectively, and the black contours show the Hα line emission). The offsets between the BCG, X-ray peak, and Hα peak suggest that the current locus of greatest cooling in the hot ICM is separated from the central galaxy nucleus and raise the question of whether they can affect the feedback cycle. From *Pasini et al. 2021, ApJ, 911.*

Contacts: myriam.gitti@unibo.it, fabrizio.brighenti@unibo.it, francesco.ubertosi2@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Radio and X-ray connections in cool core galaxy clusters*

Supervisor: Myriam Gitti (DIFA)
Co-Supervisors: Francesco Ubertosi (DIFA), Fabrizio Brighenti (DIFA)

Scientific Case:

Relativistic particles and magnetic fields permeating the intracluster medium (ICM) of galaxy clusters are best traced by diffuse radio sources extending for hundreds of kpc (*Feretti et al 2012, A&AR*; *Van Weeren 2019, SSRv*). In cool-core galaxy clusters (characterized by a central temperature drop and no signs of recent mergers, e.g., *Hudson et al. 2010 A&A*) it is possible to find "radio phoenices" and "radio mini-halos".

Radio phoenices are extended sources possibly linked to old episodes of activity of cluster-central radio galaxies. The electrons powering the radio emission are thought to have been re-energized by compression due to turbulence in the ICM. The fossil plasma has an ultra-steep spectrum ($\alpha \approx 2$, with flux density $S(\nu) \propto \nu^{-\alpha}$), suggestive of synchrotron aging, and usually has a complex morphology (*de Gasperin et al. 2015, MNRAS*; *Mandal et al. 2020, A&A*). Despite their importance to understand the interplay between thermal and non-thermal phenomena in galaxy clusters, very few sources of these kind are known.

Mini-halos are characterized by steep spectra ($1 \leq \alpha \leq 1.5$) and amorphous shapes and are typically extended to 100 - 200 kpc from the center (e.g., *Gitti et al. 2004, A&A*; *Feretti et al 2012, A&AR*). Their origin is still unclear; among several models, it has been proposed that ICM oscillations ("sloshing") in the cluster potential might power the non-thermal radio emission (e.g., *Zuhone et al. 2016, JPlPh*), since mini-halos typically appear confined within the sloshing region (e.g., *Giacintucci et al. 2010, ApJ*). Alternatively, active galactic nucleus (AGN) feedback may also provide turbulent re-acceleration due to the jets inflating bubbles and driving shock waves in the plasma (e.g., *Bravi et al. 2016, MNRAS*). A third possibility is a combination of the two: the main driver for the creation of mini-halos could be AGN activity injecting turbulence and relativistic particles in the ICM, while sloshing motions would drive the overall shape of the mini-halos (*Richard-Laferrière et al. 2020, MNRAS*). The only way to discriminate between the different scenarios is a multifrequency study of these sources: sensitive and resolved radio observations can constrain the properties of mini-halos, whereas X-ray analysis of the ICM can probe the process injecting turbulence in the clusters' hot medium.

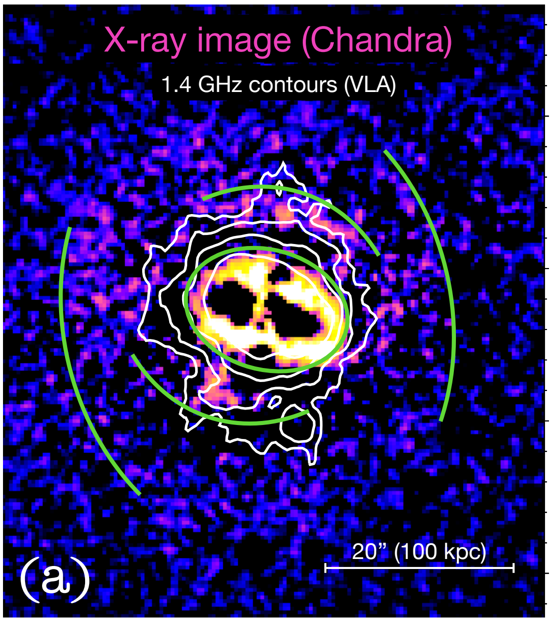


Figure 1: X-ray Chandra image of the cool core cluster RBS797, with 1400 MHz VLA contours overlaid in white showing the mini-halo. The shock fronts are indicated with green arcs (adapted from Ubertosi et al., 2023, ApJ). The radio and X-ray comparison reveals that the mini-halo is confined within the middle shock fronts, supporting the idea that AGN feedback may influence the properties of the diffuse emission.

Outline of the Project:

To understand the thermal and non-thermal interplay in cool core clusters it is crucial to combine X-ray data, that probe the thermal properties of the cluster environment, with multi-frequency radio data of radio phoenices and mini-halos, that probe the properties of the non-thermal components of the ICM (relativistic particles and magnetic fields).
The aim of the PhD project comprises two parallel investigations:

1. **Clarify the formation channels of mini-halos**: our group has been a leader research team in the field for two decades, providing both theoretical models and pioneering observational studies (*Gitti et al. 2002, 2004, A&A*; *Gitti et al. 2007 A&AL*) up to more recent investigations (*Gitti et al. 2018, A&A*; *Ignesti et al., 2020a, A&A*). An ideal system to finally grasp the details of the origin of these sources is the galaxy cluster RBS797, which hosts a diffuse radio source classified as a mini-halo (*Gitti et al. 2006, A&A*). Using deep *Chandra* observations, we recently unveiled that its ICM has been strongly perturbed by the activity of the central AGN, whose jets inflated multiple X-ray deficient cavities and drove three concentric pairs of shock fronts in the ICM (*Ubertosi et al. 2021, ApJL*; *Ubertosi et al. 2023 ApJ*). The radio mini-halo appears to be caged within the shock fronts (see Fig. 1). Interestingly, the 144 MHz – 1400 MHz spectral index flattens toward larger distances, close to the middle shock. These are tantalizing indications of a connection between the AGN activity and the diffuse source, specifically that the jet-driven shock fronts may have shaped the radio emission (*Bonafede et al. 2023, A&A*). However, uncertainties in the spectral index prevent a definitive confirmation of this result. To solve the puzzle of the origin of the radio source, the PhD candidate will use new sensitive JVLA observations at 6 and 9 GHz in combination with archival X-ray and radio data to: (a) verify the spectral index radial trend; (b) measure the radiative age of the radio emission and compare it with the shock age; (c) measure the polarization properties and the magnetic field intensity.
2. **Trace the thermal and non-thermal interplay using radio phoenices**: revived synchrotron sources are excellent probes of magnetic fields and reacceleration mechanisms. Our group has recently worked on different examples of these sources by combining X-ray and radio observations (mainly *Chandra*, JVLA, GMRT and LOFAR; e.g., *Ubertosi et al. 2021, MNRAS*; *Ignesti et al., 2020b, A&A*). We also identified other cool core clusters with X-ray and radio observations that reveal candidate radio phoenices with ultra-steep radio spectra. The PhD candidate will analyze the existing observations to measure the morphological and spectral properties of these sources, as well as determine the dynamical state of their host clusters from X-ray data.

Overall, *the PhD project is aimed at understanding the thermal and non-thermal interplay in cool core galaxy clusters, which bears the information on the thermodynamic structure of the ICM, magnetic fields, turbulent reacceleration efficiency, and relativistic particles*. The PhD candidate will measure spectral indices and polarization properties of the diffuse sources, radio and X-ray morphologies, ICM temperature, density, and pressure gradients. The PhD activities will be conducted in collaboration with international researchers. The PhD candidate will also propose for X-ray (*Chandra*) and radio (JVLA, uGMRT, MeerKAT, LOFAR) observations of candidate radio phoenices and mini-halos, to push forward the knowledge of these objects and pave the way for future radio telescopes that are expected to detect hundreds of these radio sources (as SKA; e.g., *Gitti et al. 2018, A&A*). They will also propose for complementary follow-up XRISM observations to directly measure the turbulence of the ICM and link this crucial information with the theoretical models of turbulent reacceleration. Depending on the student interests, numerical simulations can be developed to compare the observed data with detailed computational modelling.

Contacts: myriam.gitti@unibo.it, francesco.ubertosi2@unibo.it, fabrizio.brighenti@unibo.it

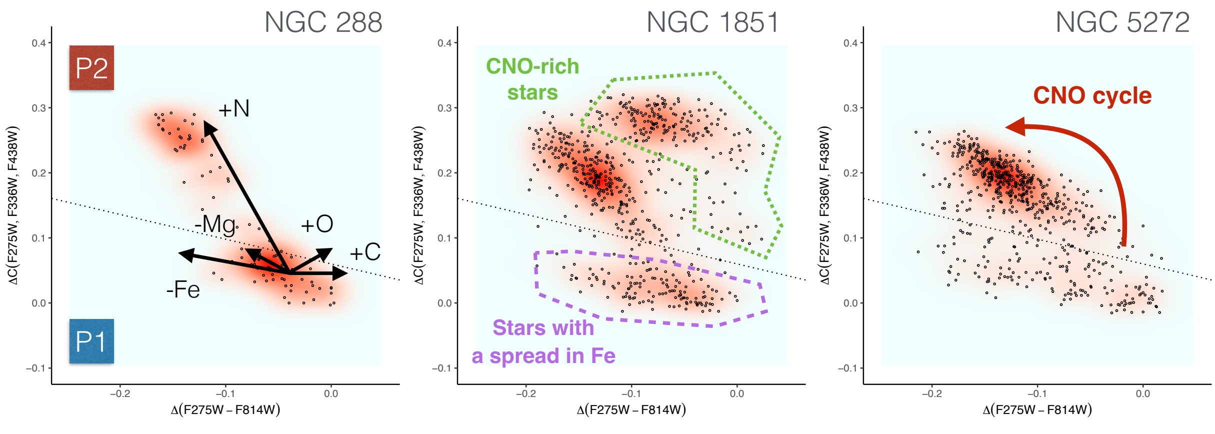
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *A data-driven approach for Multiple Stellar Populations*
Supervisor : Prof. Carmela Lardo (DIFA)
Co-Supervisor : Prof. Alessio Mucciarelli (DIFA)

Scientific Case: Stars in globular clusters (GCs) display varied light element compositions: some are rich in He, N, and Na but poor in O and C, contrasting with others that resemble field stars. These are known as MPs, with the first population (P1) showing standard abundances and the second (P2) enriched in N and Na (Gratton et al. 2012). This enrichment reflects processes not expected in low-mass stars, suggesting that P2 stars may arise from material shed by the first generation, possibly mixed with unprocessed gas, though the exact mechanisms remain unclear. Although self-enrichment models explain some aspects of MPs, they fall short in aligning with various critical observations, prompting a reevaluation from a broader perspective (Bastian & Lardo 2018).

Specific filters in imaging can discern stellar chemistry — The HST's HUGS survey (Piotto et al. 2015) introduced the chromosome map (CMs; see figure) to study the MPs of Galactic GCs using filters F275W, F336W, F438W, and F814W, revealing links between P2 star fractions, chemical variations, and GC mass that questioned traditional beliefs (Milone et al. 2017). Another HST study on the Magellanic Clouds explored clusters between 15 Myr to 10 Gyr, discovering that clusters over 1.5 Gyr have MPs, while younger ones do not, challenging MPs cosmological origins (Martocchia et al. 2018; Cadelano et al. 2022).



This figure illustrates GCs characterized by similar metal content but distinct CMs. The stars within these clusters are categorized as P1 or P2, with the separation occurring along the boundary denoted by a dotted line. Among the clusters examined, NGC 288 serves as a standard example, displaying a homogeneous P1 population and an extended P2 population. The left panel of the figure highlights the influence of light-element variations on the colors of these stars (Milone et al. 2018). In contrast, NGC 1851 and NGC 5272 exhibit increasing levels of complexity. In these GCs, we observe elemental variations within both P1 and P2 subgroups. Stars located within the green dotted polygon feature an enhanced CNO sum, potentially coupled with variations in iron content (Marino et al. 2019). GCs showing this additional sub-population have been proposed to represent former nuclei of dwarf galaxies that were accreted by the Milky Way (Da Costa in 2016). Stars found within the purple dashed polygon show intrinsic variations in iron (Legnardi et al. 2022; Lardo et al. 2022, 2023), while their C, N, and O abundances remain within the expected range. *This observation contradicts the predictions of MP scenarios, where P1 stars are expected to have uniform compositions and P2 abundances are changed by CNO cycle.The source of the iron spread and the CNO-enhanced subpopulations remains a mystery, and further investigation is essential, as it promises valuable insights into the formation ofGCs and their MPs.*

Chromosome maps are powerful but expensive — CMs are invaluable tools for studying abundance variations across many stars, yet they are costly. To date, CMs are available for only 57 GCs from the HUGS project and a handful in the Magellanic Clouds

(Saracino et al. 2020). Their reliance on the F275W filter observations makes them HST-time intensive, given the challenge of achieving the needed signal-to-noise ratio. As the HST is the only mission with top-tier UV capabilities and no upcoming missions on the horizon, extending our dataset to areas like the inner Galaxy's reddened GCs or remote regions appears unlikely. Furthermore, CMs typically cover cluster cores, limiting our understanding of sub-population spatial distribution, particularly as older GCs in these areas might no longer exhibit early formation traces.

Outline of the Project: While pivotal in understanding galaxy evolution, GCs remain enigmatic, particularly regarding the origin of their MPs with unique elemental compositions. With MPs now observed in diverse stellar systems, a detailed examination is essential to understand their formation mechanisms. Key questions arise: *Do we have a complete database for comparing models with GC elemental abundances? Can combining photometric and spectroscopic data offer a richer view of MP chemistry? What is the relationship between chemical variations and cluster properties? Are these variations born from stellar internal processes, or do we need to consider alternative explanations?*

To address the MP complexity, the project aims to introduce machine learning (ML) technology to the study of MPs for the first time. ML algorithms – known for their robust pattern recognition capabilities – will be applied to determine stellar parameters and abundances of GC stars using multi-band, wide-field imaging. This project employs two increasingly complex approaches to derive parameters and abundances.

1. The initial phase involves exploring approaches that rely on predicted magnitudes and colors as outlined in previous work (Lardo et al. 2018).
2. In a more ambitious stage, the project will utilize simulated space-based images from instruments like the HST and the JWST (Kuntzer et al. 2016). The final ML models will then be applied to previously unseen data.

The project's outcomes will facilitate statistical studies on the evolution of the MPs over time and across different parameter spaces. The goal is to discover unforeseen patterns and trends in MP properties and establish a basis for future models for their origin. This approach offers many advantages over a traditional one:

- it provides parameters and abundances for stars in the HUGS catalogs, while CMs offer qualitative insights into the variation ranges. Essentially, it serves as a cost-effective spectroscopic extension of the HUGS survey.
- It provides this information for clusters/stars which do not possess the measurements in the set of filters required to build the CMs. Such a study expands the study of MPs chemical properties across a wide volume in the Local Group and outer regions of Galactic GCs, serving as a cost-effective extension for imaging surveys(Stetson et al. 2019).
- It enables the automatic and unbiased classification of stars (P1, P2, extended P1, etc), eliminating the necessity for visually inspecting CMs. Additionally, it streamlines the process of selecting objects deemed suitable for further spectroscopic follow-up.

Contacts:

carmela.lardo2@unibo.it
alessio.mucciarelli2@unibo.it

PhD project in ASTROPHYSICS

Title of the Project:
Cosmological exploitation of the statistical properties of Cosmic Voids

Supervisor: Prof. Federico Marulli
Co-Supervisors: Dr. Sofia Contarini, Prof. Lauro Moscardini

Scientific Case:
A significant fraction of the Universe volume is made up of almost empty space regions, that emerge between the filaments and the walls of the *Cosmic Web*. These low-density patches of the Universe are known Cosmic Voids and provide one of the most powerful, though yet largely unexplored, cosmological probes. Thanks to their huge sizes – up tens of megaparsec - and low-density interiors, voids constitute unique cosmic laboratories to investigate the physical properties of **dark energy**, as well as **modified gravity theories**, **massive neutrinos**, **primordial non-Gaussianity** and **Physics beyond the Standard Model**. The current and upcoming spectroscopic galaxy surveys will flood us with a huge volume of data, allowing us to significantly enlarge the cosmic void catalogues currently available, up to large redshifts. Cosmic voids are now being recognized as core cosmological probes in next-generation experiments.
This PhD project is aimed at fully exploiting the primary large-scale statistics of the cosmic void population, that is the **size function**, the **density** and **lensing profiles**, and the **spatial clustering of voids**. The PhD student will firstly investigate different void detector algorithms, with the goal of maximizing the purity and completeness of the void samples, as well as to accurately characterize the sample selections. Standard statistical methods, as well as the newest Machine Learning techniques will be considered to optimize the data analysis pipelines. New simulated catalogues of cosmic voids shall be constructed in different cosmological scenarios to test the efficiency of the void detectors and check for systematic uncertainties in the cosmological analysis.
The PhD student will then analyse real data sets and provide new cosmological constraints from the probe combination of the main cosmic void statistics. The catalogues will be extracted from both current data sets, such as the final SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS), and ongong galaxy spectroscopic and photometric samples, as the ones from the European Space Agency (ESA) **Euclid mission**.

Outline of the Project:
The PhD project is organised in the following phases:
- Implementation of **new void detector algorithms**, including Machine Learning based methods, and comparison with existing available codes.
- Implementation of new software tools to **measure all primary statistics of cosmic voids: size function, lensing profiles, void clustering**.
- Implementation of **likelihood modules** to extract cosmological information from single void statistics and probe combinations.
- Test of the data analysis pipelines on mock void catalogues extracted from **standard and beyond-ΛCDM cosmological simulations**.

- Construction of **new real cosmic void catalogues**.
- **Cosmological analysis** on real cosmic void catalogues.
- **Forecasting** the constraining power of next-generation photometric and spectroscopic void samples.

Contacts:

Sofia Contarini (sofia.contarini@unibo.it)
Federico Marulli (federico.marulli3@unibo.it)
Lauro Moscardini (lauro.moscardini@unibo.it)

PhD project in ASTROPHYSICS

Title of the Project:
Cosmology with Bayesian deep neural networks to learn the properties of the Cosmic Web

Supervisor: Prof. Federico Marulli
Co-Supervisors : Prof. Lauro Moscardini, Dr. Alfonso Veropalumbo

Scientific Case:
In the last decades, the exponential growth of data drastically changed the way we do science. This data tsunami led Astrophysics in the so-called Big Data Era. Standard cosmological analyses based on abundances, two-point and higher-order statistics of specific extra-galactic tracer populations – such as e.g. galaxies, galaxy clusters, voids - have been widely used up to now to investigate the properties of the *Cosmic Web*. However, these statistics can only exploit a sub-set of the whole information content available.
The proposed PhD project aims to enhance the scientific utilization of current and future galaxy surveys, taking advantage of the newest data analysis techniques to assess the properties of the large-scale structure of the Universe. Specifically, the goal is to **develop a new Bayesian deep neural network for cosmological analyses**. The implemented supervised machine learning infrastructure will be trained and tested on simulated catalogues in different cosmological frameworks, and then applied to current available data sets, such as e.g. BOSS, eBOSS, DESI. In the next future, the developed neural network will be used to analyse the data provided by the European Space Agency (ESA) **Euclid satellite**.
The primary scientific goals of this PhD project are to provide independent constraints on the **dark energy equation of state parameters** and to **test Einstein's General Theory of Relativity**. The PhD student will acquire high-level knowledge on the modern statistical techniques to analyse large extra-galactic data sets and extract cosmological information. Moreover, he/she will become familiar with the latest deep learning techniques for data mining, which will be explored for the first time in a cosmological context. The new implemented algorithms will be included in the CosmoBolognaLib, a large set of *free software* C++/Python libraries for cosmological calculations.

Outline of the Project:
The PhD project is organised in the following phases:
- **Construction of a large set of dark matter mock catalogues in different cosmological frameworks** using fast techniques, such as the ones based on Lagrangian Perturbation Theory.
- Application of subhalo abundance matching (**SHAM**) and/or halo occupation distribution (**HOD**) techniques to populate the dark matter catalogues with galaxies and galaxy clusters.
- Implementation of **new standard and Bayesian deep neural network infrastructures**.
- **Training and testing** of the neural networks on mock galaxy and cluster catalogues.

- **Comparison of the cosmological constraints from neural network and standard probes**, such as e.g. the ones from two-point and three-point correlation functions of galaxies and galaxy clusters.
- **Utilization of the new machine learning tools on available data sets** to derive independent cosmological constraints.
- Application of the tools on larger mock catalogues to provide **forecasts for next-generation galaxy redshift surveys**.

Contacts:
Federico Marulli (federico.marulli3@unibo.it)
Lauro Moscardini (lauro.moscardini@unibo.it)
Alfonso Veropalumbo (alfonso.veropalumbo@uniroma3.it)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Exploring Gravity Models with gravitational redshifts in galaxy cluster environments

Supervisor: Prof. Federico Marulli
Co-Supervisor: Prof. Lauro Moscardini

Scientific Case:
Current and future wide-field spectroscopic and photometric surveys (e.g., KiDS, Euclid, LSST) present a unique opportunity to significantly increase the number of known galaxy clusters and explore previously uncharted territories at both low mass ($M \sim 10^{14} M_{sun}$) and high redshift ($z > 1$). The scientific interest in these new samples of galaxy clusters is twofold. Firstly, the abundance and clustering of these structures provide crucial constraints on cosmology, as the cluster population carries information about the statistical distribution of initial fluctuations, their subsequent growth, and the dynamics of dark matter halo collapse. Secondly, these clusters serve as invaluable laboratories for studying the evolution of galaxies in dense environments across different epochs.
Furthermore, **galaxy clusters offer natural cosmic laboratories for conducting direct measurements of gravitational redshifts**, enabling tests of gravitational theories on megaparsec scales. Specifically, the gravitational redshift effect can be inferred from the distribution of peculiar velocities of cluster member galaxies as a function of their transverse distance from the cluster center. However, achieving the required precision for definitive tests of General Relativity versus alternative gravity theories has been hindered by the lack of sufficiently large and dense samples of galaxy clusters and associated cluster member galaxies. This limitation is expected to be overcome with the wealth of data from upcoming missions such as the ESA Euclid Telescope and the NASA Nancy Grace Roman Space Telescope.
The objective of the proposed PhD project is to leverage the new galaxy and cluster spectroscopic samples expected in the near future to conduct **novel tests of gravitational theories using gravitational redshifts in galaxy clusters**. The PhD student will initially construct and characterize new spectroscopic cluster catalogues, focusing on key properties such as cluster centers and the positions of cluster member galaxies. New software tools will be developed to compute these measurements and conduct the necessary statistical analyses. The validity of these pipelines will be verified using simulated catalogues to identify and address potential systematic uncertainties. The newly implemented algorithms will be made publicly available through the CosmoBolognaLib, a comprehensive suite of *free software* C++/Python libraries for cosmological calculations. Ultimately, the PhD student will deliver new constraints on gravitational theories, potentially distinguishing among various alternative gravity frameworks.

Outline of the Project:

- Construction and characterization of **new photometric and spectroscopic catalogues of galaxy clusters and cluster member galaxies** from simulated and real data sets.
- Implementation of **novel algorithms to measure and model the peculiar velocity distributions** of cluster member galaxies.
- Integration of the developed software into the **CosmoBolognaLib**.
- Investigation of all potential **systematic uncertainties** affecting the analysis.
- Application of the model to real datasets to derive **new constraints on gravity theories**.
- Application of the model to mock catalogues of next-generation missions to provide **forecasts** for future analyses.

Contacts:

Federico Marulli (federico.marulli3@unibo.it)
Lauro Moscardini (lauro.moscardini@unibo.it)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Stars as laboratories for testing fundamental physics

Supervisors : Andrea Miglio (DiFA, UniBo), Oscar Straniero (INAF-OAAb)

Scientific Case:

The high temperature and density that develop within the cores of evolved stars, from red giants to supergiants, make them ideal sites to investigate deviations from the standard models describing the behaviour of matter in extreme conditions, which are often not accessible by current laboratory experiments.

In this context, a growing amount of scientific papers discuss peculiar properties of hypothetical weakly interacting particles, by comparing stellar models predictions to several astronomical observables.
For instance, axions are pseudo-scalar particles predicted by several non-standard theories. They provide the most elegant solution to the so-called strong CP problem, i.e, the conservation of the charge-parity symmetry in processes that involve strong interactions. If they exist, axions may have a great impact on cosmology (they are good dark matter candidates) and on stellar evolution. Indeed, they may be produced in hot stellar interiors through their coupling with standard particles, like photons or electrons. In this framework, the most stringent constraints to the strength of the axion-photon coupling comes from the lifetime of core-helium-burning stars (Ayala et al., 2014), while the most stringent constraint to the axion-electron coupling is provided by the luminosity of the red-giant tip (Straniero et al., 2020; Capozzi & Raffelt, 2020). In addition to axions, other feeble particles, e.g., dark photons, may also be produced by thermal processes in stellar interiors and, hence, probed with this technique. The same method may also provide hints on the electromagnetic properties of standard particles, e.g. the neutrino magnetic moment (Capozzi & Raffelt, 2020).

The constraints obtained so far are, however, limited by the effective reliability of our stellar models and by the scarce direct information we have on the internal structure of stars. The situation has now changed, and detailed constraints on the internal structure of red giants are now available thanks to the detection and interpretation of their resonant oscillation frequencies (asteroseismology), offering a unique opportunity to get important hints on various new-physics hypotheses.

Outline of the Project:
During the 3-yr project, the student will:
- Quantify the effect of non-standard particles on the internal structure and evolution of red-giant stars and on their pulsational spectra. The student will familiarise with stellar evolution and pulsation codes and, crucially, with the current uncertainties pertaining to stellar modelling (year 1).
- Devise observational tests needed to set limits on the cross-section describing the interaction of non-standard particles with stellar matter (year 2,3). These tests will

explore both potential direct seismic signature of non-standard particles and indirect signatures that are expected to become significant as a result of reducing, thanks to seismic constraints, other uncertainties in current models (e.g., extension of the convective core, core angular momentum).

The student will be involved in large international collaborations, in particular in the ESA PLATO mission consortium (launch 2026 https://platomission.com/, https://www.esa.int/Science_Exploration/Space_Science/Plato) and in the proposal of next-generation asteroseismic missions such as HAYDN (http://www.asterochronometry.eu/haydn/)

The nature of the project is such that the student should be happy coding and interpreting results from numerical simulations of stellar evolution, analysing and manipulating data. Familiarity with stellar evolution would be highly beneficial.

Contacts:

Prof. Andrea Miglio
andrea.miglio@unibo.it
https://www.unibo.it/sitoweb/andrea.miglio
https://www.asterochronometry.eu

Prof. Oscar Straniero
oscar.straniero@inaf.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Exploiting Gravitational Waves as cosmological probes in view of the new upcoming large GW and galaxy surveys

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Andrea Cimatti

Scientific Case: Modern cosmology is currently undergoing an exciting yet problematic time. After the discovery of the accelerated expansion of the Universe (Riess et al., 1998, Perlmutter et al. 1999), many of the cosmological probes currently identified as 'main' (Cosmic Microwave Background, Baryon Acoustic Oscillations, Supernovae Type Ia) experienced a period of continuous technological and theoretical development that lead them to percent accuracy; however, as a consequence this lead to a tension between early- and late-Universe measurements, that are currently pointing to values of cosmological parameters at odds by more than 4 sigma (see e.g. Verde et al. 2019). It is therefore now crucial to go beyond standard probes and explore alternative probes that can help to resolve this tension. Gravitational waves (GW) are amongst the most promising emerging cosmological probes in the near future (see Moresco et al. 2022). These astrophysical phenomena provide us a clean measurement of the distance to the source completely independent on cosmological models, only relying on General Relativity. However, to be used as standard sirens, it is necessary to associate to these events a redshift, as firstly proposed by Schutz (1986). This association can be either direct (bright sirens, as for the case of GW170817) or statistical (as for the case of dark sirens, see e.g. Palmese et al., 2021, LIGO Scientific Collaboration et al., 2021). In this Ph.D. Thesis, we propose to explore techniques to maximize the scientific return of analysis of GW as cosmological probes by improving on current analysis by including in the analysis new observational features, exploring the constraints that can be set by current data, forecasting the impact of the new upcoming large GW (Advanced LIGO-Virgo, Einstein Telescope, ...), and preparing a framework to be prepared to analyze the expected new data by the LIGO/Virgo collaboration.

Outline of the Project: The field of GW cosmology has recently started and is gaining a growing attention in the cosmological community. For this reason, many different aspects are still worth exploring, especially in the use of GW as dark sirens, like the impact in the derivation of cosmological parameters of the galaxy catalog used to cross-correlate the EM counterpart of the GW, of the accuracy in the redshift estimates, of the completeness of the catalog, of the assumed distribution of BBH masses, of extending the GR framework in the analysis. While some seminal works are being recently published, it is crucial to assess many of these aspects to establish GW as robust cosmological probes. At DIFA, we recently developed a public GW analysis SW (CHIMERA, in collaboration with national and international colleagues), and in this Ph.D. Thesis we propose to extend those by including new features as discussed above, with the following goals: (i) integrate in the GW codes a Bayesian framework to estimate the Bayes factors for the various models explored and study different models, (ii) study and characterize current public catalogs

(GLADE+, DESI, …), (iii) analyze the impact of different properties in the catalogs (completeness, accuracy of the redshift estimates) on the cosmological parameters accuracy, (iv) take advantage of the expertise at DIFA in generating mock galaxy catalog (CosmoBolognaLib) to develop a framework to produce ad-hoc simulated galaxy catalogs for GWs to forecast the performance of the combination of future spectroscopic surveys (e.g. Euclid) and GW observatories (e.g. Einstein Telescope), (v) apply the developed framework to current and simulated data, to provide forecasts on the constraints on the expansion history of the Universe, also in combination with other cosmological probes.

Contacts:
prof. Michele Ennio Maria Moresco
Associate professor
Department of Physics and Astronomy – University of Bologna
address: via Gobetti, 93/2, 40129, Bologna
email: michele.moresco@unibo.it - phone: 051/2095775

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Towards a comprehensive clustering analysis: maximizing the scientific return through the combination of lower-order and higher-order correlation functions in configuration and Fourier space

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Massimo Guidi, Federico Marulli

Scientific Case: The analysis of the clustering of galaxies has recently become one of the fundamental tools in Modern Cosmology to probe the distribution of Large Scale Structure. It retains cosmological information of the primordial Universe in the form of peculiar matter over-densities that appear around 100 Mpc/h. These features are called baryon acoustic oscillations (BAOs), and can be used as standard rulers to constrain the expansion history of the universe. In Fourier space, they appear as wiggles in the power spectrum, P(k), while in configuration space, they appear as a distinctive peak around $r\sim100$ Mpc/h in the two-point correlation function (2PCF). For these reasons, since the beginning of the century galaxy clustering has become one of the main cosmological probes, and several spectroscopic surveys both from the ground (e.g. BOSS, eBOSS) and from space (e.g. Euclid) have been developed to exploit it at its best.
Historically, the field has been divided into two approaches, either by working in Fourier space (where the modelization is easier, but handling observational effects such as the footprint is more complicated) or in configuration space (with opposite pros and cons). Moreover, up to a few years ago most of the research has been focused on two-point statistics (P(k) and 2PCF), and only a few efforts have been made on higher-orders (bispectrum, B(k), and three-point correlation function, 3PCF).
While it is predictable that to maximize the scientific exploitation and accuracy in cosmological parameter constraint the combination of all these measurements should be combined in a joint analysis, no attempt has been currently made in this direction. Only one work explored the combined constraints on 2PCF+P(k) (Sanchez et al. 2016), finding promising results. Furthermore, recent works have addressed bridging the gap between Fourier and configuration space higher-order modelling. This has opened the path to a comprehensive joint likelihood including lower- and higher-order analysis to mitigate possible systematics and increase the statistical significance of the clustering analysis.
However, in view of the upcoming large spectroscopic surveys that will revolutionize the field with unprecedented statistics of galaxies, it is crucial to take this step.

Outline of the Project: The aim of this Ph.D. Thesis will be to develop a framework for the combined analysis of clustering 2-point and 3-point statistics both in configuration and in Fourier space, namely the 2-point correlation function, the 3-point correlation function, the power spectrum and the bispectrum. Building on the wide expertise of our group on clustering analysis (both on 2-point and 3-point correlation functions) and on the combination of different statistics, the Ph.D. student will base his/her work on the CosmoBolognaLib libraries (Marulli, Veropalumbo & Moresco, 2016), working to extend

these to provide a comprehensive pipeline for the joint analysis of 2PCF+3PCF+P(k)+B(k).
The work will be divided into the following steps:

1. Development of a pipeline for the analysis of 2PCF + P(k) and 3PCF + B(k), starting with a focus on the constraints that can be obtained on bias parameters;
2. Assessment of the cross-covariance between the various statistics (exploiting a theoretical and/or numerical approach);
3. Exploring the constraints that can be obtained on cosmological parameters expanding the modeling through emulators developed with Machine Learning algorithms: this will allow us to explore the constraints at the BAO and/or nonlinear scales;
4. Extend the pipeline for the joint analysis 2PCF+P(k)+3PCF+B(k) analysis;
5. Application of the pipeline to simulated and real data, assessing the gain in constraining power obtained with the full combination and the relative contribution of each term, and providing forecasts and new constraints on bias and cosmological parameters (e.g. exploring Euclid simulation and real data datasets like eBOSS and catalogs of cluster of galaxies);
6. Test the new developed pipeline on real Euclid data.

The Ph.D. student will approach and strengthen knowledges in galaxy clustering and Large Scale Structure, and will be also introduced in Italian and international collaborations that focus on this field (e.g. Euclid).
This work could provide a fundamental tool not yet explored in view of the large spectroscopic surveys that are taking data in this moment (like Euclid), and will be extremely timely to extend the current capabilities in an uncharted but exciting territory. From this point of view, the developed pipeline will be applied to the state-of-art data that will be available at the time needed.

Contacts:
prof. Michele Ennio Maria Moresco
Associate professor
Department of Physics and Astronomy – University of Bologna
address: via Gobetti, 93/2, 40129, Bologna
email: michele.moresco@unibo.it - phone: 051/2095775

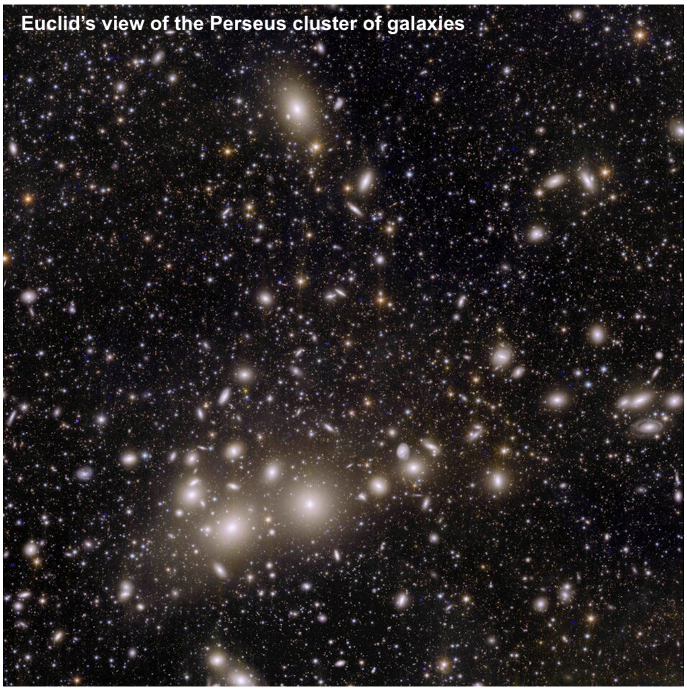
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Statistical Tools for Cluster Cosmology Studies in the ESA-Euclid Era Mission

Supervisor: Lauro Moscardini (DIFA)
Co-Supervisors: Carlo Giocoli (INAF-OAS), Federico Marulli (DIFA), Massimo Meneghetti (INAF-OAS)

Scientific Case:
The successfully launched ESA-Euclid telescope is expected to deliver much data to the scientific community. Galaxy cluster cosmology is expected to increase the constraining power to test general relativity further to the two primary cosmological probes: galaxy clustering and weak gravitational lensing. Thanks to the exquisite data we are already receiving, the developed processing functions will be able to measure with extreme precision both the redshifts and the shapes of the large number density of photometric galaxies – approximately 30 galaxies per square arcminutes. The primary objective will be to measure the clustering and the weak lensing to trace the growth of structures from the present time up to high redshifts: $z \approx 2$. In addition, the Galaxy Cluster Science Working Group has defined the guidelines for using the photometric galaxy catalog to identify groups and clusters of galaxies (Sartoris et al. 2016, Adam et al. 2019) thanks to two algorithms: AMICO and PZWav. The weak lensing data, associated with the tiny distortion of the shape of background galaxies lying beyond the clusters, will be of primary importance in weighting the cluster mass. Using clusters as a cosmological probe, their abundance and their spatial distributions as a function of redshift, rely on the bias and the accuracy with which we can measure their mass and combine them with complementary cosmological data.

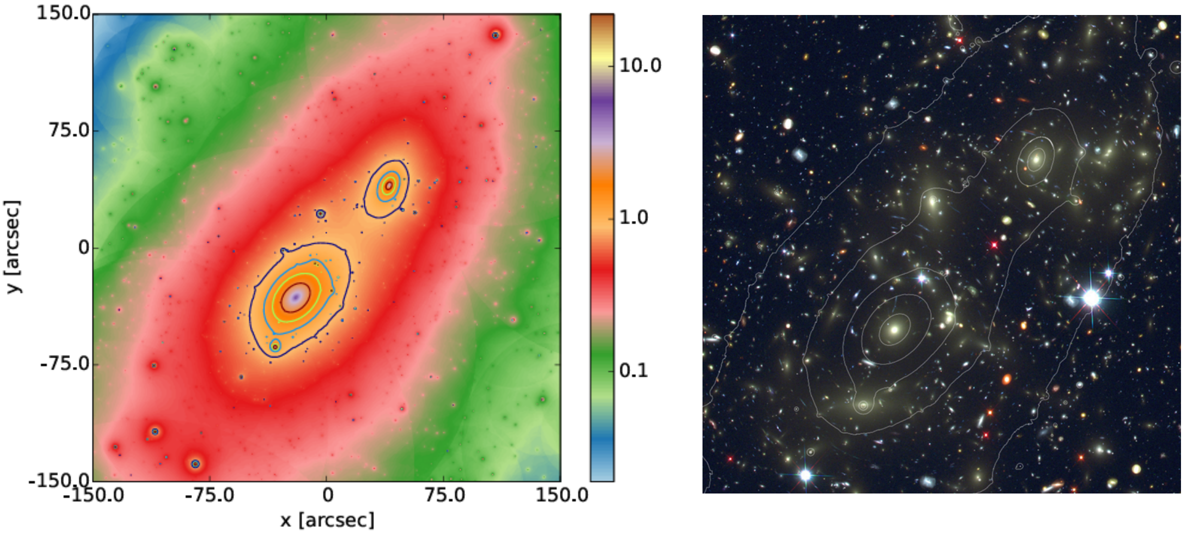


In recent years, the Bayesian, machine learning, and forward model methods have acquired great statistical interest in astrophysics and cosmology. Those represent the state-of-the-art tools that will be used to analyze upcoming data from the approaching wide-field photometric data.

Outline of the Project:

The student will be fully involved in scientifically exploiting the cluster cosmological studies within the Euclid Consortium. She/he will join the Consortium, becoming a member of the Clusters of Galaxies, Strong Lensing, and Weak Lensing Science Working Groups.

The activities will be devoted first to constructing dedicated weak lensing simulations of clusters extracted from hydrodynamical runs and pseudo-analytical realizations using the MOKA code (Giocoli et al. 2012). The image below, from Meneghetti et al. (2017), displays the projected mass density distribution of the cluster mass generated by MOKA (left panel) and the SkyLens image simulation on the right.



The simulations will be useful for several applications. For example, they will be a valuable training set to build deep learning models for the statistical inference of several cluster properties (mass, concentration, triaxiality, etc.) based on the observed lensing signal. In addition, they will be used to study how deep learning methods compare to more traditional methods for measuring the same properties (for example, by fitting projected shear profiles). Furthermore, their analysis will inform us of mass biases depending on other cluster properties. An interesting extension of the lensing simulations could be deriving additional simulated observables for the same clusters (e.g., X-ray emission, SZ signal, optical and near-infrared imaging, etc). Such complementary data would allow us to investigate the impact of possible selection effects on the measurement of cluster structural properties.
Thus, by developing the simulated dataset, the student will acquire know-how on weak lensing, multi-wavelength observations, and fast statistical methods.
In a second step, he/she will then improve and optimize the cosmological pipeline starting from the cluster catalogs of the Euclid Collaboration (EC) and develop a mathematical forward model to derive cosmological parameters and combine them with the corresponding clustering and weak lensing constraints (To, Krause et al. 2021). The CLOE pipeline already developed within the EC, together with the results from the first part of the project, will represent the starting point for this section. The student will also be involved in studying and modeling the group and cluster weak lensing profiles using the developed statistical methods and benchmark possible dependencies on cosmology.
The framework of this Ph.D. project within an international scientific community will allow the student to improve his/her expertise, learn new methods, and possibly construct networking for a successful future in science research. A 3-6 month visit for scientific collaboration in one of the international institutions involved in the collaboration will be planned during the Ph.D. period.

Contacts: Lauro Moscardini (lauro.moscardini@unibo.it), Carlo Giocoli (carlo.giocoli@inaf.it), Federico Marulli (federico.marulli3@unibo.it), Massimo Meneghetti (massimo.meneghetti@inaf.it)

PhD project in ASTROPHYSICS

Title of the Project: A multi-wavelength view of galaxy clusters and AGN from Euclid and XMM-Newton

Supervisor: Lauro Moscardini (DIFA)
Co-Supervisors: Micol Bolzonella (INAF-OAS), Stefano Ettori (INAF-OAS), Cristian Vignali (DIFA)

Scientific Case:
The **Euclid** telescope is a space mission developed by the European Space Agency (ESA) with contributions from NASA, aiming at observing 14000 deg^2 with grism NIR spectroscopy and photometry across visual and NIR wavelengths. While its primary goal is to investigate the mysteries of dark energy and dark matter, Euclid's observations in 3 deep fields promise a lasting legacy across various aspects of astrophysics, from galaxy clusters to AGN. Launched on July 1st 2023, Euclid started the survey operations on February 14th, 2024, marking the beginning of a six-year programme.

XMM-Newton, short for X-ray Multi-Mirror Mission, is an X-ray observatory launched by the European Space Agency (ESA) in December 1999. It is one of the most powerful X-ray telescopes ever built, designed to observe high-energy phenomena in the universe with unprecedented sensitivity and spatial resolution.

Recently, a **XMM Multi Years Heritage programm**e (PI M. Pierre, co-PI M. Bolzonella, B. Maughan, S. Paltani) has been awarded with 3.5Ms to obtain the coverage of the 10deg^2 of the Euclid Deep Field Fornax at 40ks depth.

The **Fornax Deep Field** will be the deepest among the 3 Euclid Deep Fields; the concurrent XMM observations promise to deepen our understanding of AGN and galaxy clusters,, including: deep characterisation of Euclid-detected clusters and their selection function; robust measures of cluster scaling relations to $z = 1.5$ and the group regime; the study of rare clusters and AGN in a variety of environments; and revealing the link between AGN feedback and star formation to $z > 3$.

The project will be carried out in the framework of the Euclid collaboration, including ~2000 international scientists. In Bologna (DiFA and INAF institutes) there is a large and lively research group dealing with many different aspects of the science that will be enabled by Euclid data.

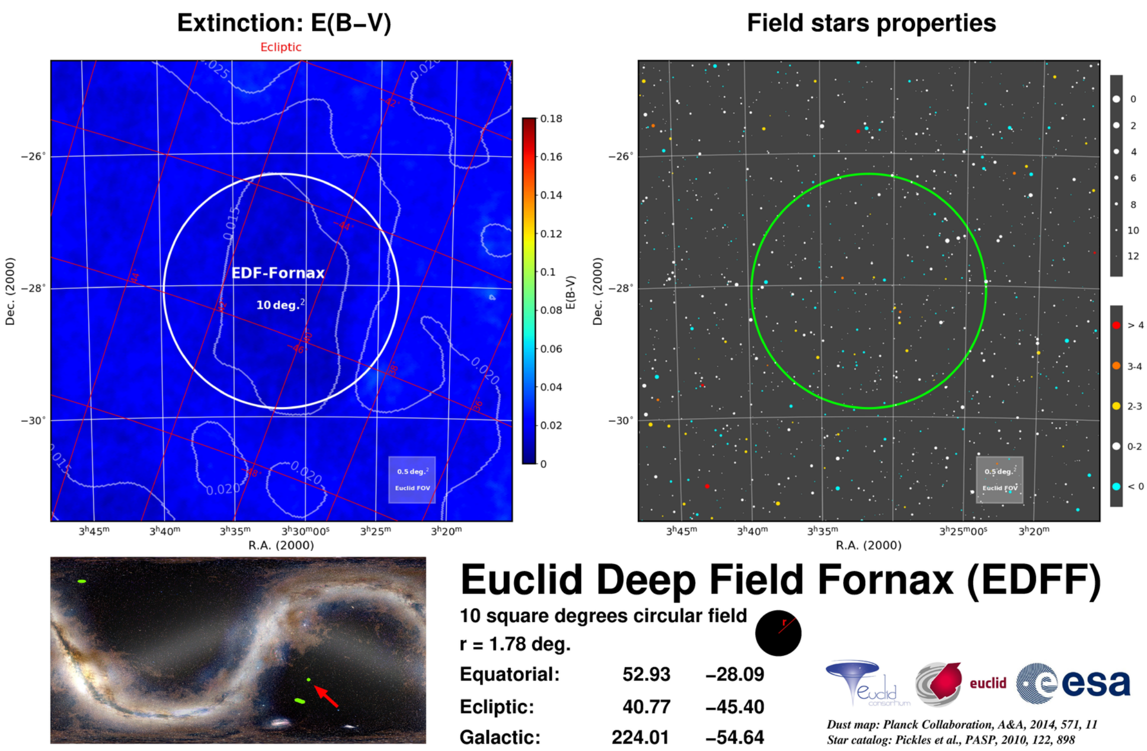
Outline of the Project:
The project, to be discussed with the PhD candidate, can include some of the following aspects.

For AGN:

- Characterisation of the sources with SED fitting, X-ray spectral and hardness-ratio analyses to obtain a preliminary list of obscured sources also at high redshift. This would help constraining the black hole accretion rate density as a function of cosmic time;

- Use of the vast multi-wavelength dataset to build a training sample to develop machine learning tools for automatic source classification and characterisation (including photometric redshifts and physical properties of the host galaxies);
- Study the co-evolution of AGN and their host galaxies, in particular, how AGN transit from an initial heavily dust-enshrouded phase to a 'blow-out' phase (when radiation and outflows from the accreting SMBH blow away the dust and gas);
- Determine the AGN incidence in galaxy clusters and its evolution, to understand the different evolution in the field and in dense environments.
- Use AGN as tracers of massive and growing halos in the early Universe to search for galaxy overdensities around X-ray AGN to identify proto-clusters and large-scale structures at $z > 2$;
- Comparison with the expected forecast of simulations and models.

For clusters of galaxies:
- Characterisation of X-ray and optical properties, their differences to analyse the systematics affecting the selection at different wavelengths, and comparison with simulated ones;
- Cross-identification of clusters identified in Euclid and XMM to constrain both the baryonic and dark matter components;
- Predictions and analysis of the scaling relations (between temperature, luminosity, richness) to study the feedback and the connection between the cooling of ICM, fuelling of star formation, accretion of AGN, and presence of energetic outflows; these feedback processes are fundamental to understand the galaxy stellar mass function and are a critical ingredient of cosmological simulations.



Contacts: Lauro Moscardini (lauro.moscardini@unibo.it), Micol Bolzonella (micol.bolzonella@inaf.it), Stefano Ettori (stefano.ettori@inaf.it), Cristian Vignali (cristian.vignali@unibo)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

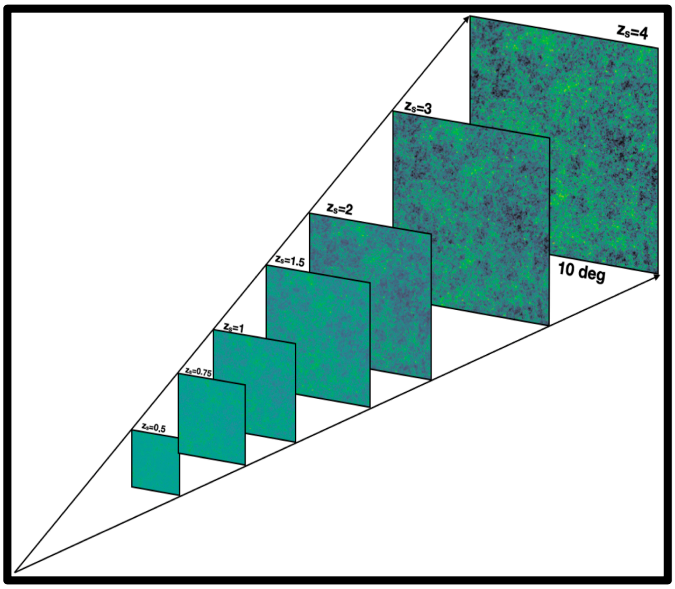
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Detection of galaxy clusters, peaks and cosmic voids in Weak Lensing Simulations: paving the way to the ESA-Euclid Mission data

Supervisor: Lauro Moscardini (DIFA)
Co-Supervisors: Carlo Giocoli (INAF-OAS), Federico Marulli (DIFA), Massimo Meneghetti (INAF-OAS)

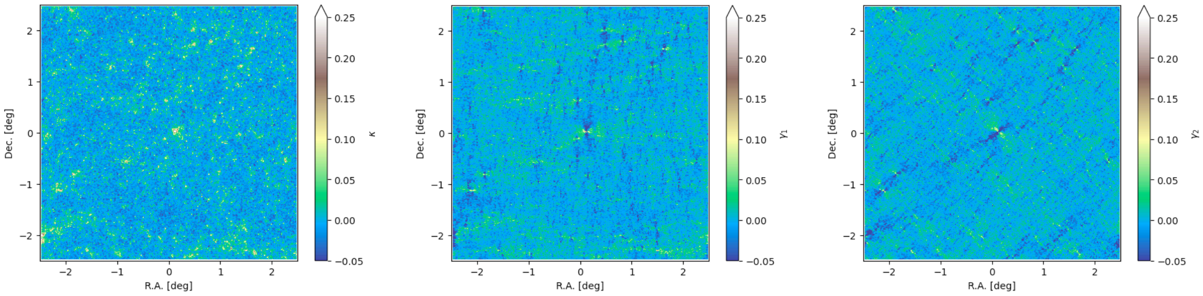
Scientific Case:
Future wide-field surveys, like the successfully launched ESA-Euclid telescope, are expected to deliver much data to the scientific community. The primary cosmological probes that Euclid will use to probe cosmology are **weak gravitational lensing** and galaxy clustering. The tiny modification of the intrinsic galaxy shapes, caused by the interposed matter density distribution, allows us to trace the growth of structure during cosmic time up to high redshift. The large number density of galaxies and sky coverage (ng=30 galaxies per square arcmin observed on 15,000 square degrees) expected to be collected by the ESA-Euclid telescope will allow us to constrain cosmological parameters with unprecedented precision. This will open the possibility of using the weak lensing signal to detect and characterize overdense and underdense regions: galaxy clusters, peaks, and cosmic voids. The accuracy and precision of these methods require the development of dedicated weak lensing light-cone simulations (see Figure) to improve the methods and modelings based on emulators.



Weak Lensing light-cone simulations will be used as cosmic reference laboratories in this PhD Thesis. Considering the available simulations in our group, the build cones have a field-of-view with an aperture varying from 5 to 10 deg on a side and extending up to z=4.
The large data set of N-Body runs performed adopting different cosmological models and the various corresponding light-cone realizations will give us the possibility to build emulators for weak lensing high-order statistics: voids and peaks present in the projected matter density field

Outline of the Project:
The Ph.D. student will dedicate the initial period of her/his project to constructing dedicated **weak lensing Euclid simulations** using the tools and data sets available in our group: MOKA libraries (Giocoli et al. 2012), MapSim (Giocoli et al. 2014) and WL-MOKA (Giocoli et al. 2017). This will be done using projected matter density distributions from cosmological

numerical simulations and shooting rays using the ray-MapSim routine (Giocoli et al. 2015). The constructed shear and convergence maps will be used to extract an Euclid-like shear catalog of sources, as shown in the figure below (convergence on the left and the two components of the shear on the central and right panel, respectively), assuming the expected nominal depth of 24.5-24 mag in the VIS instrument of Euclid, building up a dedicated database.



Knowing the underlying galaxy cluster population, the Ph.D. student will test the performance of an optimal filter-based algorithm to identify **galaxy clusters** using the shear catalogs and correlate it with the derived weak lensing peaks. The feasibility of the method has already been demonstrated in a series of works (Pace et al. 2007 - as a pioneering analysis). The tool must be scaled and tested on more accurate and updated simulations. This second activity will allow us to construct an iterative cluster weak lensing selection function required to complement the photometric one (Sartoris et al. 2016) and derive complementary constraints on the main cosmological parameters.

As galaxy clusters trace the overdensities of the projected matter density distribution, cosmic voids delineate the under-densities. As a third activity, the student will develop a new algorithm to **identify and characterize cosmic voids** using weak lensing information, paving the way toward new research topics (Fang et al. 2018; Sanchéz et al. 2017; Melchior et al. 2012).

The work activities performed during the PhD period will be based on various international collaborations our group in Bologna has and framed within different ESA Euclid Collaboration work packages (https://www.euclid-ec.org). In this way, the student will have great opportunities to interact with diverse scientists, giving her/him the appropriate skills for a fruitful career. A 3-6 month visit for scientific collaboration in one of the international institutions involved in the partnership will be planned during the PhD period.

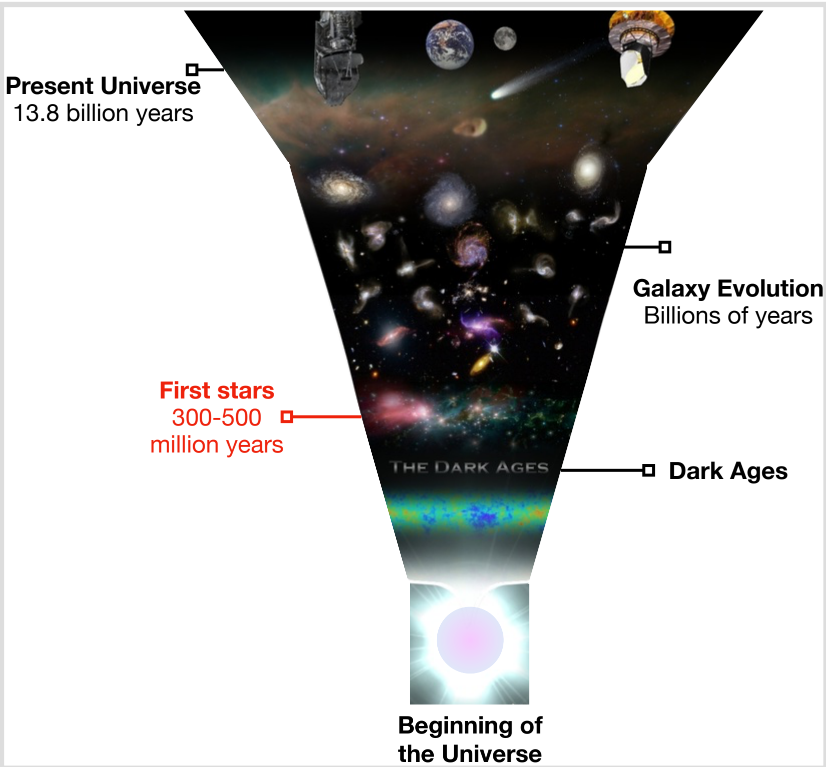
Contacts: Lauro Moscardini (lauro.moscardini@unibo.it), Carlo Giocoli (carlo.giocoli@inaf.it), Federico Marulli (federico.marulli3@unibo.it), Massimo Meneghetti (massimo.meneghetti@inaf.it).

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Near-Field Cosmology with Metal-Poor Stars*
Supervisor : Prof. Alessio Mucciarelli (DIFA)
Co-Supervisor : Prof. Carmela Lardo (DIFA)

Scientific Case: The Big Bang yielded hydrogen (H), helium (He), and a limited amount of lithium (Li). Subsequent to this, stars took on the role of both producing and recycling metals across successive stellar generations within galaxies. This process, integral to cosmic evolution, led to the synthesis of an increasing array of elements over time. The advent of the first stars, known as Population III stars, occurred approximately 300-500 million years after the Big Bang. Notably, these objects played a key role in concluding the Dark Ages of the Universe through their input of light and ionising radiation. Despite their importance, our understanding of Pop III stars hinges predominantly on theoretical models and numerical simulations, given the impracticality of direct observation (Klesser & Glover 2023).



Old stars tend to be metal-poor The most metal-poor objects born from the ashes of the first stars, formed when the cosmos was almost devoid of metals. For example, the most metal-poor star identified to date boasts an iron abundance of approximately one part in

10’000’000 relative to solar levels. Consequently, stars characterised by exceptionally low metallicities also signify an extraordinarily old age.

Overall, this implies that studying old, metal-poor stars in the local universe provides us with the most detailed insights into the physical and chemical properties that regulate the formation of primordial stars. This understanding is derived from an analysis of their kinematics and chemical abundances, carefully examined through high-resolution, high-signal-to-noise spectra.

Outline of the Project: Investigating the properties of long-lived stars within the Milky Way offers additional perspectives on fundamental processes. This includes insights into early-time physical conditions, the nature of the first stars, and the synthesis of elements, encompassing the associated nucleosynthetic processes. Such knowledge is unattainable through the study of distant and faint objects at high redshifts (Norris & Frebel 2015).

The envisioned Ph.D. project will leverage top-tier spectra acquired through the Very Large Telescope and data sourced from the Gaia space mission. Employing cutting-edge techniques for the analysis of abundances in high-resolution spectra, the aim is to extract precise stellar parameters and abundances for a substantial and statistically relevant sample of stars exhibiting very low metal content. The precise chemical tagging of metal-poor stars presents an opportunity to address numerous unresolved challenges in modern astrophysics, such as:

- **Formation and evolution of the Galaxy** — By integrating chemical abundance data with kinematics sourced from Gaia, we can enhance our comprehension of the formation process of the Galactic Halo and the mechanisms governing the assembly of our Galaxy.

- **The hierarchical build-up of MW stellar halo from small dark-matter dominated systems** — Dwarf galaxies contain a significant fraction of the known metal-poor stars. Through a comparative analysis of their abundances with those found in the MW Halo, we can systematically evaluate the universality of primordial chemical evolution. This study also enables a deeper comprehension of the interconnection between dwarf galaxies and the building blocks contributing to the formation of the Halo (Jablonka et al. 2015).

- **The nature of the first supernovae** — The comparison between the abundances of very metal-poor stars and theoretical yields from Population III supernovae serves to constrain star formation at high redshift and the properties of first supernovae. A detailed chemical analysis of neutron-capture elements is imperative for elucidating details of the nucleosynthetic processes involving neutron capture (Sneden 2003). This includes discerning aspects such as the impact of rapid neutron capture on the abundance of post-iron-peak elements, the occurrence frequency of neutron star mergers, and the dynamics of mass transfer in binary systems (van de Voort 2019).

Contacts:

carmela.lardo2@unibo.it

alessio.mucciarelli2@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:

Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies

Supervisor : Prof. Alessio Mucciarelli (DIFA)
Co-Supervisors : Prof. Carmela Lardo (DIFA)

Scientific Case:

According to the Λ cold dark matter cosmological paradigm, structure formation proceeds bottom-up, as small structures merge together to build up the larger galaxies we observe today. The Milky Way is a prime example of this formation mechanism, as first demonstrated by the discovery of the Sagittarius dwarf spheroidal galaxy in the process of disruption (Ibata et al.1994), then by halo stellar streams crossing the solar neighborhood (Helmi et al. 1999), and more recently by the discovery of stellar debris from Gaia-Enceladus, revealing the last significant merger experienced by our Galaxy (Helmi et al. 2018). As a result of such merger events, not only stars, but also globular clusters were accreted.
The chemical composition of stars is a powerful tool to reconstruct the history of the parent galaxies and their possible merger events. In fact, the amount of different metals in a star acts as a powerful "*DNA probe*" that allows us to trace the genealogy of each star and to distinguish those formed in other galaxies and only later added to the main building. This approach has been recently used to identify for the first time the relic of a past merger event occurring in the Large Magellanic Cloud (Mucciarelli et al. 2021, Nature Astronomy).

Outline of the Project:

The PhD project is aimed at describing the chemistry of Milky Way satellites (like the Sagittarius dwarf galaxies, the Large and Small Magellanic Clouds), nearby isolated dwarf galaxies and ultra-faint dwarf galaxies. The chemical DNA of these galaxies will be compared with that of the Milky Way in order to reconstruct the chemical enrichment history of these galaxies. Two key questions will be addressed in this project,

- **Assembly history of the massive satellites -** the chemistry of field and globular cluster stars of the most massive Milky Way satellites (i.e. the Magellanic Clouds) will be used to reveal possible past merger events occurring in their history and to search for the missing satellites of these galaxies, predicted by Λ cold dark matter simulations. The search for past merger events in these galaxies is an exciting hot topic in modern astrophysics that is taking its first steps, only one merger event has been discovered so far in these galaxies (Mucciarelli et al. 2021).
- **The early evolution of the interacting satellites** – the chemical properties of long-lived, metal-poor, old stars provide detailed insights into the early ages of these galaxies when they evolved in isolation and before they start to interact each other. These rare stars will allow us to understand the impact of first supernovae in different galactic environments and enhance our comprehension of the first Gyr of life in these systems.

The project will benefit from proprietary and archival high-resolution spectra obtained with ground-based telescopes (i.e. VLT, LBT,Subaru,Keck) that will be analysed to derive a complete screening of the chemical properties of these stars (see Minelli et al. 2021a,b for some examples of the adopted approach).

Foreseen milestones and deliverables

- at least one refereed paper per year in the best impact-factor astronomical journals;
- dissemination of the project results at international astronomical conferences;
- collaboration with world-renowned experts in spectroscopy of resolved stellar populations

Contacts:

alessio.mucciarelli2@unibo.it
carmela.lardo2@unibo.it

PhD project in ASTROPHYSICS

Title of the Project: *Hydrodynamic simulations of Terzan 5 and BFFs*

Supervisor: Carlo Nipoti (UniBo)
Co-supervisors: Francesco Calura (INAF-OAS), Francesco Ferraro (UniBo)

Scientific Case

Understanding the origin of globular clusters (GCs) and their multiple stellar populations is a major challenge in modern astronomy. Peculiar cases are represented by the so-called Bulge Fossil Fragments (BFFs) Terzan 5 and Liller 1 that, at variance with ordinary GCs, display multiple sub-populations of stars with large differences in age and in iron content. The complex abundance pattern of these systems indicates an enrichment history characterised by multiple star formation episodes, separated by time intervals as long as a few Gyrs. This non-trivial feature is unexpected for a GC and various explanations have been proposed: besides the possibility that they are remnants of long-lived clumps, most of which eventually merged to form the Bulge, they may also be accreted nuclear star clusters formed in dwarf galaxies (Bastian & Pfeffer 2022) or the result of existing GCs accreting gas and forming a new stellar generation. The aim of the present project is to investigate the latter possibility.

Outline of the Project

To explain the formation of the complex stellar populations of Terzan 5 and its analogues, we propose to use three-dimensional hydrodynamic simulations and model the encounter of an old stellar population with a reservoir of cold gas, such as a molecular cloud.

We propose to use a customized version of the RAMSES code (Teyssier 2002) which includes basic yet realistic physical ingredients, such as radiative cooling, star formation, feedback and chemical enrichment (Lacchin et al. 2021; Calura et al. 2022).

The results of the simulations will be compared with the observational properties of these systems, including their abundance pattern and colour-magnitude diagrams, in an effort to make significant progress in our understanding of the complex history of the BFFs.

Contacts: carlo.nipoti@unibo.it , francesco.calura@inaf.it, francesco.ferraro3@unibo.it

References:

- Bastian N., Pfeffer J., 2022, MNRAS, 509, 614
- Calura F., Lupi A., Rosdahl J., Vanzella E., Meneghetti M., Rosati P., Vesperini E., et al., 2022, MNRAS, 516, 5914
- Lacchin E., Calura F., Vesperini E., 2021, MNRAS, 506, 595
- Teyssier R., 2002, A&A, 385, 337

Bologna, 25/2/2024

PhD project in ASTROPHYSICS

Title of the Project: *Global stability of stellar discs with dark matter halos*

Supervisors: Carlo Nipoti (UniBo), Luca Ciotti (UniBo), Silvia Pellegrini (UniBo)

Scientific Case:

Thin stellar discs are prone to global instability and bar formation. The formation and evolution of the bar is an open research field, addressed by means of N-body simulations since the early 1970s (e.g. Ostriker and Peebles, 1973). Some criteria have been studied to understand the conditions for the development of global instabilities in the stellar disc leading to bar formation. The most common global stability parameter, due to Ostriker and Peebles (1973), is $t=T/|U|$, where T is the ordered kinetic energy of the system and U is the total gravitational energy. An alternative global stability parameter has been proposed by Efstathiou et al. (1982): $t^*=T^*/|W^*|$, where now T^* is by definition the stellar order kinetic energy and W^* is the trace of the gravitational interaction energy tensor of the stars in the total gravitational potential.
Whether either of these parameters is sufficient to describe the global stability of stellar discs in the presence of dark matter halos is still debated.

Outline of the Project:

In this project, the student will study the global stability of stellar discs in the presence of dark matter halos, using high-resolution N-body simulations. Following the approach of the preliminary explorations of Caravita (2022) and Cantarella (2023), the student will construct N-body realizations of equilibrium two-component galaxies, with stellar disc and dark matter halos. The considered systems will differ greatly ranging from simpler cases of thin discs with "frozen" dark matter halos to more realistic cases of thick discs with "live" dark matter halos, for which a careful study of the distribution functions will be necessary. The stability of these systems will be studied by following their evolution with N-body simulations. The results of the simulations, combined with the measurement of the parameters t and t* of the initial conditions, will allow to draw conclusions on the proposed stability criteria and possibly also to construct new stability criteria.

Contacts: carlo.nipoti@unibo.it , luca.ciotti@unibo.it, silvia.pellegrini@unibo.it

References:

- Ostriker, J. P. and Peebles, P. J. E., 1973, ApJ, 467-480
- Efstathiou, G., Lake, G. and Negroponte, J., 1982, MNRAS, 199, 1069-1088
- Caravita, C., 2022, PhD thesis, University of Bologna
- Cantarella S., 2023, Master thesis, University of Bologna

Bologna, 25/2/2024

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Simulations of the collisional evolution of globular clusters with Monte Carlo methods

Supervisor: Carlo Nipoti (UniBo)
Co-supervisor: Raffaele Pascale (INAF-OAS)

Scientific Case:
Globular clusters are the perfect environment to study the evolution of stellar systems over timescales where the effects of collisionality on their dynamics cannot be neglected. Indeed, globular clusters are dynamically old, dense agglomerates of stars with relaxation time (i.e. the time needed by the stars to redistribute efficiently their energy due to two body encounters) way shorter than the age of the Universe, which makes them susceptible to processes of energy equipartition, mass segregation and gravitational evaporation. In this context, Monte Carlo (Henon 1971) algorithms are a special family of methods, alternative to and less computational expensive than N-body simulations, suited to follow the long time, dynamical evolution of stellar systems once the integrals of motion of their tracers are perturbed to account for two-body interactions.

Outline of the Project:
The PhD student will develop a novel version of the orbit-averaged based Monte Carlo method presented in Sollima and Mastrobuono Battisti (2014), optimized to model spherical stellar systems as globular clusters with the inclusion of binaries, stellar evolution and external tidal force fields (e.g. Sollima and Ferraro 2019,). The code, first developed in Fortran77, will be partially ported in Python and complemented by flexible tools to handle the statistical and graphical analysis of typical outputs of the codes, as well as new features to account in the models for central intermediate massive black holes, a continuous mass spectrum in the initial distribution of stars, and more general initial conditions. From the model it is possible to compute observables to te directly compared with observations of real globular clusters. The software will be then used to model the dynamical evolution of a set of globular clusters orbiting around the Milky Way to study mass segregation and the effect of massive dark remnants (e.g. black holes) at the center of the system.

Contacts: carlo.nipoti@unibo.it , raffaele.pascale@inaf.it

References:

- Hénon M.H., 1971, ApSS, 14, 151
- Sollima A., Mastrobuono Battisti A., 2014, MNRAS 443, 351
- Sollima A., Ferraro F.R., 2019, MNRAS, 483, 1523

Bologna, 25/2/2024

PhD project in ASTROPHYSICS

Title of the Project: *Local gravitational instability of stratified rotating fluids*

Supervisor: Carlo Nipoti (UniBo)

Scientific Case:
Fragmentation of rotating gas systems via gravitational instability is a crucial mechanism in several astrophysical processes, such as formation of planets in protoplanetary discs and of star clusters in galactic discs. Gravitational instability is fairly well understood for infinitesimally thin discs, but the thin-disc approximation is often not justified. Nipoti (2023) presented new 3D instability and stability criteria, which can be used to determine whether and where a rotating system of given 3D structure is prone to clump formation. For a vertically stratified gas disc of thickness h_z, the instability criterion takes the form Q_3D<1, where Q_3D, depending on h_z and on the local gas properties, is a 3D analogue of the classical 2D Toomre (1964) Q parameter. The Q_3D criterion has been recently applied to observed galactic gaseous discs by Bacchini et al. (in prep), and extended to multicomponent discs by Nipoti et al. (in prep).

Outline of the Project:
The PhD student will study the local gravitational stability properties both of observed systems and of models. As far as observed systems are concerned, the student will extend the study of Bacchini et al. (in prep) by considering the 3D stability and instability criteria to thick multi-component discs for which we have information on the vertical structure, ranging from protoplanetary discs to gaseous galactic discs at low and high redshift.
As far as models are concerned, the student will build numerical (as in Nipoti and Binney 2005) and analytic (as in Sotira 2022) equilibrium models of self-gravitating rotating fluids and will apply to these models the 3D gravitational stability criteria. The analytic results will be complemented by numerical hydrodynamic simulations aimed at studying the non-linear behaviour of the models.

Contacts: carlo.nipoti@unibo.it

References:

- Bacchini C., Nipoti C., et al. (in prep.)
- Nipoti C., 2023, MNRAS, 518, 5154
- Nipoti C., Binney J., 2015, MNRAS, 446, 1820
- Nipoti C., Caprioglio C., et al. (in prep.)
- Sotira, S., 2022, "Analytic models of self-gravitating rotating gaseous tori with central black hole", Master Thesis, University of Bologna
- Toomre A., 1964, ApJ, 139, 1217

Bologna, 25/2/2024

PhD project in ASTROPHYSICS

Title of the Project: Exploring binary millisecond pulsars in globular clusters through optical/near-infrared observations.

Supervisor: C. Pallanca
Co-Supervisors: M.Cadelano, F.R. Ferraro, B. Lanzoni

Scientific Case:
Globular clusters (GCs) are old, compact and dense gravitationally bounded stellar systems. They are collisional systems and are the main efficient factories of peculiar stellar populations, as millisecond pulsars (MSPs). In fact, the number of MSPs per unit mass in the Galactic GC population is significantly larger than in the Galactic field. MSPs are stable and fast rotating neutron stars, emitting a collimated radio periodic signal (e.g. usually described with the "lighthouse" model) with typical periods of milliseconds. The main formation scenario of these object is commonly known as the "recycling scenario", according to which a NS is spun up by mass accretion in a binary system. In this context MSPs companions are expected to be He-white dwarfs (WD, i.e. the residual cores of the peeled companions that recycled the pulsars). However, even if several He-WD companions have been already identified as companions to MSPs, a zoo of unique objects is emerging. This is not surprising considering the host environment. Indeed, the active innermost regions of GCs may perturb the canonical evolution of these binary systems.

Outline of the Project:
The unprecedented power of recent radio telescopes (e. g. MeerKAT and FAST) is propelling MSPs detection into a thriving era. Taking advantage of this significant improvement, the Galactic globular cluster MSP population has increased by >80% in the last three years. Therefore, the time is ripe for a thorough study of companions to binary MSPs in GCs. A photometric search for companions to binary MSPs hosted in GCs will be performed. For each target, the astrometric position, the CMD location and the presence of variability will be investigated. To achieve these goals, multi-filter and multi-exposure data-set at high spatial resolution, such as proprietary and archival JWST and HST observations, will be used. The optical identification of the companion stars to MSPs will bring key information on the nature, the physical parameters, the evolutionary processes and the recycling mechanisms occurring in these systems. Secondly, the full characterization, in synergy with radio and X-ray studies, of binary MSPs will enable a wealth of groundbreaking scientific applications, such as testing general relativity and alternative theories of gravity, studying stellar and binary evolution and constraining the equation of state of matter at the nuclear equilibrium density, thus eventually opening a new window in the domain of Fundamental Physics research. Finally, linking the current properties of the MSP population to the internal dynamical status of the host cluster, will clarify the role that the most massive objects/binaries play in the evolution of GCs, and, vice versa, the role that internal dynamical processes play in the evolutionary path of these objects. Such a project will set the stage of our understanding of the population of MSPs.

Main external Collaborators: Emanuele Dalessandro (OAS-Bo), Paulo Freire (Max Planck Institute – Germany), Craig Heinke (Alberta University, Canada), Scott Ransom (NRAO – USA), Alessandro Ridolfi (OAC)

Contacts: cristina.pallanca3@unibo.it

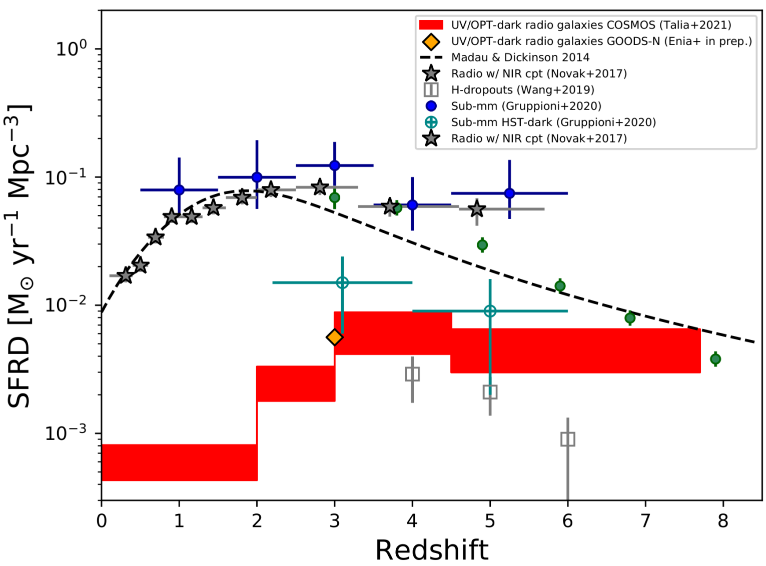
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Illuminating the Dark Side of Cosmic Star Formation*
Supervisor : Francesca Pozzi (DiFA)
Co-Supervisor : Margherita Talia (DiFA), Isabella Prandoni (INAF-IRA).
Collaborators : galaxy evolution groups at UNIBO-DIFA, INAF-OAS and INAF-IRA.

Scientific Case One of the main questions in modern astrophysics is understanding the formation of galaxies and their evolution through cosmic time. Our current knowledge of cosmic star-formation history during the first two billion years is mainly based on galaxies identified in rest-frame ultraviolet light. However, this population of galaxies is known to under-represent the most massive, dust-obscured galaxies, whose contribution to the star-formation is still largely unknown, especially at high redshift (z>3). In recent years, the quest for such galaxies has been carried on by adopting various selection criteria at different wavelengths, from mid-infrared (Wang et al. 2019), to sub(mm) (Franco et al. 2018, Gruppioni et al. 2020) and radio (Talia et al. 2021, Enia et al. 2022, Gentile et al. 2024), but a consensus has not been reached yet.

Outline of the Project The objective of the project will be to determine the contribution of dust-obscured, massive galaxies to the cosmic star-formation rate density and to study their physical properties and evolutionary path.
The project will consist of the following steps.



(1) A search for galaxies that are invisible at optical and near-infrared wavelengths using two different approaches: the so-called H-dropout technique (Wang et al. 2019) and a radio selection (Talia et al. 2021). In particular, the search will be conducted by taking advantage of the private radio data from the MIGHTEE survey (Hale et al. 2023, https://www.mighteesurvey.org/), a large radio survey of ~20 deg2 at 1.4GHz performed with the MeerKAT radio

telescope in South Africa (the SKA precursor) and complemented by the wealth of multi-wavelength dataavailable in those fields.

(2) Estimating redshift and physical properties (LIR, SFR, stellar mass, extinction, dust temperature) of the selected galaxies with SED fitting. This will allow to understand if these dusty obscured galaxies are the "*missing progenitors*" of massive and passive galaxies found at high-z (Valentino et al. 2020b) on the way to quench their star-formation.

(3) Estimating their contribution to the cosmic star formation density (see Figure) and comparison with theoretical models (Illustris, Millennium) to investigate the evolutionary links with present-day ETGs.
The PhD student will learn how to make the best use of multi-wavelength data and to interpret them to constrain galaxy physics and evolution. He/she will gain expertise in observing proposal writing and will acquire the scientific expertise and independence needed to continue her/his career successfully at international level.
Finally, thanks to this PhD project, the student will become a member of an international team aimed at studying dusty obscured galaxies and their role in shaping galaxy evolution. https://sites.google.com/inaf.it/rsnirdark/

Contacts: f.pozzi@unibo.it; margherita.talia2@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Exploiting the Euclid Legacy for galaxy evolution with ELSA

Supervisor : Margherita Talia
Collaborators : ELSA team members

Scientific Case:
Euclid is an ESA space telescope launched in July 2023, designed to understand the nature of dark energy and dark matter. To achieve this, Euclid is observing over a third of the sky with high resolution imaging and spectroscopy, which will establish "the" reference map of the extra-galactic celestial sphere for decades to come. The giant archive produced will be a goldmine to study the history of the formation and growth of galaxies over the age of the Universe, driving answers to many fundamental science questions on the co-evolution of galaxies and supermassive black holes, the interaction between stars, gas, and galactic nuclei in galaxies at cosmic noon, and excelling in the discovery of rare objects including gravitational lenses.

Outline of the Project:
The main objective of this project will be the update/development of existing/new tools for spectro-photometric analysis (i.e. combining both spectroscopic and photometric data) and their application to Euclid data from the first and second data releases (DR1-DR2) in order to extract a wide range of physical parameters, including star formation history, dust emission, and metallicity, providing a complete understanding of the physical and chemical properties of the galaxies observed by Euclid.
The project will consist of the following main steps:

1) Do a complete census of existing spectro-photometric codes, to be tested and adapted to Euclid data using custom simulated photometric catalogues and spectra. If needed, develop a new tool for spectro-photometric analysis specifically tailored to the analysis of very large datasets. The application of machine learning algorithms will also be explored.
2) Test the feasibility of spectro-photometric analysis on individual galaxies and select a suitable sample from the Euclid dataset. Build stacked datasets using the codes already developed at DiFA (Quai et al., in preparation) in order to extend the analysis to the faint tail of the parameters space.
3) Perform spectro-photometric analysis on individual and stacked Euclid data and derive physical properties for different galaxy populations (i.e. "normal" star-forming galaxies, passive galaxies and AGN). Study the evolution of scaling relations (e.g. mass-age, mass-metallicity) with redshift and the possible dependence on environment.
4) Compare the results to state-of-the-art theoretical models (e.g. GAEA), in order to put them into the broader context of galaxy evolution.
5) Publish the scientific results and make the new tools available to the wider community through their implementation into the ESA datalabs.

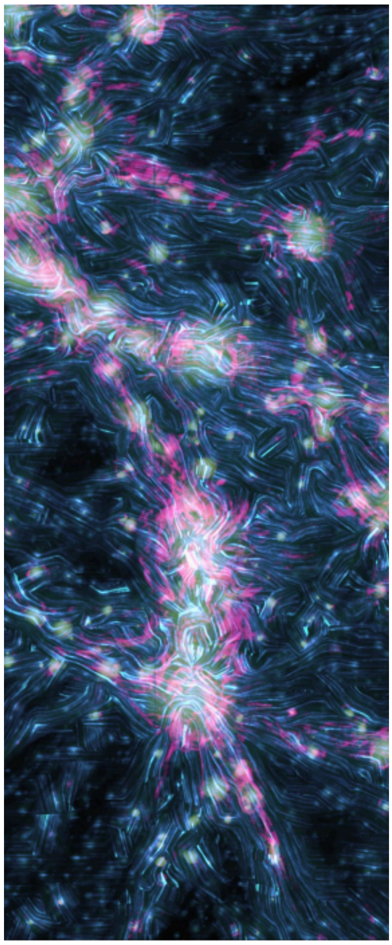
The PhD project will be carried out as part of the Euclid Legacy Science Advanced

Analysis Tools (ELSA) program, an HORIZON-EU funded project (PI: M. Talia) aimed at exploring new methodologies and creating cutting-edge pipelines, tools and algorithms in order to maximally exploit the legacy value of Euclid spectroscopic data for galaxy evolution studies. In particular, the successful applicant will work in the framework of the Work Package 2 (1D-spectra) and in close collaboration with ELSA team members both in Bologna (namely S. Quai and A. Enia at DiFA and L. Pozzetti and M. Bolzonella at INAF-OAS) and in the other institutes that are part of the collaboration. ELSA membership will give access to reserved computational resources of the cluster inside the Open Physics Hub (OPH) at DiFA. Also, the PhD student will enter the Euclid collaboration and gain priority access to all the data collected by the telescope.

Contacts: Margherita Talia <margherita.talia2@unibo.it>

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS



Title of the Project:
Advanced simulations of the Radio Cosmic Web
Simulazioni avanzate del cosmic web in banda radio
Supervisor : Prof. F. Vazza
Co-Supervisors : Dr. C. Gheller, Dr. G. Brunetti

Scientific Case: Several exciting recent low-frequency radio observations (e.g. Vernstrom et al. 2023; Cuciti et al. 2022) have called for an update of theoretical models to study how relativistic electrons are seeded on the largest scales in the Universe. Cosmological simulations are the ideal tool to test new acceleration theories as they allow us to couple the injection of relativistic particles ejected from galaxies and active galactic nuclei, with their further reprocessing by Fermi processes in astrophysical plasmas.
In order to match the large volume and level of detail proved by new radio surveys, like from LOFAR, ASKAP and MEERKAT and in preparation to the future ones by the Square Kilometre Array, new and ambitious cosmological simulations should be deployed on High Performance Computing facilities. Moreover, new numerical approaches must be tested and validated to introduce more complexity in the way we normally deal with cosmic ray astrophysics, in the sanse that we need to be able to follow the evolution of radio emitting particles in large cosmic volumes and for time scales of billions of years.
In this project, the PhD candidate will work at the design of new simulations of relativistic processes (like injection of relativistic electrons from shocks, radio jets and galactic activity) tailored to scale on tens of thousands of computing nodes equipped with modern Graphic Processing Units (GPU), and study the observable properties of state of the art models of the relativistic particle content of our Universe.

Outline of the Project: The PhD candidate will work at the design, testing and production of new large cosmological simulations optimised to run on large HPC facilities like LEONARDO at Cineca, and increase both the variety of physical mechanisms, and the total statistics of simulated objects.
The candidate will learn new numerical methods to evolve families of cosmic rays, account for their dynamical impact on the surrounding gas, and compute their observational signatures from radio waves to gamma-rays, and also include other potential signatures of strong acceleration events (e.g. in the production of neutrinos).
The candidate will be involved in the ongoing observational and numerical activities of the PI's group (https://cosmosimfrazza.eu/erc-magcow) and will have the chance of producing new exciting numerical simulations on some of the largest Supercomputers in the world. This project calls for candidates with experience (or curiosity) in numerics, theory and large-scale structure dynamics.

Contacts: franco.vazza2@unibo.it

PhD project in ASTROPHYSICS

Title of the Project: Tracing the Early Cluster Assembly with Accreting Black Holes in Enormous Lyα Nebulae at z=2−3

Supervisor: Cristian Vignali (DIFA)
Co-Supervisors: F. Vito (INAF-OAS), S. Marchesi (DIFA)

Scientific Case: Cosmological numerical simulations provide a clear picture of how dark matter drives the formation and evolution of galaxy clusters across cosmic time. A nascent cluster begins to collapse in the highest peaks of the matter density field and then grows hierarchically through a process of accretion and mergers of small haloes streaming along Mpc-sized filaments. Such "proto-clusters" (the ancestors of today's massive clusters) are usually identified as large galaxy overdensities at $z>1.5-2$. Their study provides a window into the early baryonic processes that led to the formation of today's massive galaxies and their transformation in dense environments. These processes involve galaxy mergers and interactions, fueling and growth of supermassive black holes (SMBHs) at their centers, and energy injection from SNe explosions and Active Galactic Nuclei (AGN) into the interstellar medium of cluster galaxies and the intracluster medium.

Outline of the Project: The main goals of the proposed PhD project are (a) understanding how SMBHs form and grow within early cosmic structures and (b) whether and how AGN feedback processes affect the transformation of these structures across cosmic epochs. The PhD candidate will consider proto-clusters at $z>2$ around powerful AGN selected primarily from the detection of enormous (>200 kpc) Lyα nebulae (ELANe); for these structures, a wealth of multi-band information, including data from a Chandra large program (PI: F. Vito), VLT/MUSE, HST, ALMA and SCUBA2, has been already collected. The PhD student's work will focus on (i) deriving the properties of the AGN and their host galaxies (bolometric luminosity, obscuration, stellar mass, star formation rate, etc.) and comparing them with those of field (i.e., `isolated') AGN; (ii) searching for signatures of diffuse X-ray emission that may give insights on both AGN feedback and the dynamical status of the structure, as recently carried out for the Jackpot nebula at z=2; (iii) disclosing faint AGN emission in non-active galaxy members (adopting also the X-ray stacking technique) and investigating their physical properties (e.g., star formation rate, stellar and molecular mass), to finally determine whether and how the presence of AGN activity in the same region may affect their properties.

The results will be compared with those in the literature that have been obtained in similarly overdense structures and in the field, i.e. in average density regions, as well as with the expectations from numerical simulations.

The PhD candidate will be trained in the formation and assembly of galaxy clusters, and AGN physics and demography. She/he will learn how to handle multi-band data catalogs and to analyze and interpret data from different instruments (e.g., Chandra, XMM-Newton, VLT/MUSE, HST, ALMA, JWST). She/he will gain expertise in proposal writing, acquire scientific independence, present the work at international conferences, and have the opportunity to visit renowned research Institutes and Universities.

Contacts: cristian.vignali@unibo.it; fabio.vito@inaf.it; stefano.marchesi@unibo.it.

PhD project in ASTROPHYSICS

Title of the Project: The realm of dual super-massive black holes

Supervisor: C. Vignali (DIFA)
Co-supervisors: A. De Rosa (INAF-IAPS), P. Severgnini (INAF-Brera)

Scientific Case: On the presence of AGN in dual super-massive black holes in the multi-messenger era

Outline of the Project: Hierarchical models of galaxy formation predict that galaxy mergers represent a key transitional stage of rapid super-massive black hole (SMBH) growth. Merging SMBHs are among the loudest sources of gravitational waves (GWs) in the Universe and will be detectable with the future large ESA mission LISA. Yet, the connection between the merging process and enhanced AGN activity (hence the triggering and the level of nuclear emission) remains highly uncertain, mostly affected by the lack of a thorough census of dual AGN over cosmic time. Precise demography of dual SMBHs and the occurrence of AGN activity is currently hampered by the adopted detection techniques, by sensitivity and spatial resolution issues, and by the increasing evidence that dual AGN at kpc scales are more heavily obscured than in isolated systems (e.g., De Rosa et al. 2019). Despite the intensive observational efforts to search for dual and offset AGN (where only one member of the pair is active) in the last decade or so, how common they are and the link with their host galaxy properties and close environment are still open questions. Since the detection and physical characterization of dual SMBHs at all scales are critical in the context of BH accretion history and galaxy evolution, it is mandatory to overcome the current limitations through an optimal exploitation of the complementarity between observations and numerical techniques.

The current PhD project will focus on (a) the occurrence of dual and offset AGN by cross-matching large-area optical/near-IR survey galaxy pairs/multiplets with Chandra and XMM-Newton catalogs and infer the level of nuclear activity via multi-wavelength data; (b) an extensive search for dual AGN in some of the deepest X-ray fields currently available, expanding the view to high redshift; (c) decomposition analysis of optical/NIR (LBT, VLT) data of dual AGN candidates; (d) an intensive study of the currently known dual AGN in terms of BH mass ratio and host galaxy (and environment) properties. The PhD student will also be introduced to the analysis of MUSE, ALMA, HST, VLT, and JWST data to fully characterize dual AGN and their hosts, and will be included in some of the major GW collaborations (LISA, LGWA, ET). The derived source demography and physical properties obtained through multi-wavelength data will be interpreted and placed in a coherent picture using state-of-the-art numerical simulations.
The PhD student will gain significant expertise in data analysis and interpretation and writing proposals; she/he will acquire scientific independence, present the work at national/international conferences, and have the opportunity to visit renowned research institutes and universities inside the collaboration.

Contacts: Cristian Vignali – DIFA (Bologna; Email: cristian.vignali@unibo.it);
Alessandra De Rosa – INAF-IAPS (Roma; Email: alessandra.derosa@inaf.it)
Paola Severgnini – INAF-Brera (Milano; Email: paola.severgnini@inaf.it)

PhD project in ASTROPHYSICS

Title of the Project: Shedding light on the physics of the most massive, highly accreting SMBHs at high redshift through a multi-wavelength study

Supervisor: C. Vignali (DIFA)
Co-supervisors: E. Piconcelli, L. Zappacosta (INAF-Osservatorio Astronomico di Roma)

Scientific Case: While the physics of accretion in quasars at low redshift has been widely investigated in the last decades and has provided a generally accepted picture, at high redshift the situation is far less clear. Probing accretion in luminous quasars at z=2−7 is fundamental to investigating the strict interplay between the disc UV emission and that of the X-ray emitting corona at the highest accretion rates, verifying whether different accretion-disc solutions may be at play (with relevant consequences for the seed black hole topic), and assessing, from a physical and demographic perspective, the role of quasar-driven feedback in shaping galaxies in the early times of the Universe.

Outline of the Project: In this project, accretion physics is tackled by adopting a twofold approach, namely using (i) the sample of WISE/SDSS selected hyper-luminous ($L_{bol}>10^{47}$ erg/s) quasars at z~2−4 and (ii) the sample of hyper-luminous quasars at the epoch of reionization (HYPERION, z>6), which were granted a multi-year XMM-Newton Heritage program (PI: L. Zappacosta). The BH mass range at z>6 has been extended by a further, recently accepted XMM Large Program. All of these quasars are characterized by large Eddington ratios, thus probing accretion at its 'extremes', and have multi-wavelength data allowing for a comprehensive investigation of their properties. We aim at studying (a) the nature of X-ray weak quasars at z~3 (~30% of the population) and their occurrence at earlier cosmic epochs, thus providing an interpretation in the context of accretion-disc physics of highly accreting SMBHs; (b) the relations among the X-ray luminosity, the disc/corona emission and the blueshifted velocity of the CIV line, which have direct implications for the launching mechanism of accretion-disc winds; (c) the relations between the presence of broad absorption line features in UV spectra and the multi-band spectral and photometric nuclear properties; (d) the properties of quasar host galaxies (e.g., star-formation rates, molecular gas content) via SED fitting and millimeter (ALMA) observations; (e) the nature of the radio emission, which had a widespread detection in the WISSH QSOs. Further extension of this work may include a systematic spectral analysis of z~2−4 quasars in archival Chandra and XMM-Newton observations. The properties of the analyzed quasars will be finally compared with those of local AGN to get a comprehensive view of accretion across cosmic time.

The PhD student will gain invaluable expertise in multi-wavelength data analysis (including JWST) and interpretation, in preparing observing proposals, and in presenting the work at national/international conferences. She/he will join the WISSH and HYPERION collaborations, take advantage of the interactions with researchers of Italian and foreign institutes, and pave the way for the forthcoming ground- and space-band facilities (e.g., Vera C. Rubin Observatory, Roman Space Telescope, Athena).

Contacts: C. Vignali (cristian.vignali@unibo.it); E. Piconcelli (enrico.piconcelli@inaf.it); L. Zappacosta (luca.zappacosta@inaf.it).

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: The realm of the high-redshift Universe unveiled by JWST

Supervisor: Cristian Vignali (DIFA)
Co-Supervisors: F. Vito (INAF-OAS), S. Marchesi (DIFA)

Scientific Case: In the last few years, the James Webb Space Telescope has revolutionized our view of the high-redshift Universe through the discovery of a significant number of galaxies and Active Galactic Nuclei (AGN) up to very high redshift, probing the first hundreds million years of the Universe. Among its main discoveries, JWST has been able to detect black holes down to about 10^6 $M_{\odot}$ at z>5, i.e. three orders of magnitude lower than probed by the SDSS; interestingly, most of the current JWST-detected AGN (and candidates) are host in under-massive galaxies (compared to local relations), which suggest a complex path for AGN and galaxies in reaching the local `Magorrian relation'.
Claims of accretion-related activity have been recently formulated for the Little Red Dot (LRD) population, i.e. faint AGN candidates detected by the deep JWST surveys, likely associated with red compact sources experiencing episodes of star formation. What is currently missing is a proper broad-band characterization of both AGN (candidates) and LRD populations taking advantage of the deep X-ray exposures in e.g. the CEERS, JADES, and Abell 2744 fields.

Outline of the Project: The main goals of the proposed PhD project are (a) to provide a physical characterization of the AGN thus far discovered at high redshift (z>4) by JWST using X-ray data and stacking analysis; (b) place constraints on the accretion-related activity in the LRD and galaxy population using X-ray data coupled with multi-band spectral energy distribution fitting; in this regard, a non-detection in X-ray stacked image, if coupled with detection in radio stacked data (radio-excess technique), would suggest the presence of obscuration; (c) unveil the thus-far still poorly investigated population of obscured AGN candidates at the highest redshift; this search will take advantage – when available – of JWST/MIRI data; (d) provide an updated census of the dual and offset AGN population at high redshift through a multi-wavelength approach. Furthermore, the recently granted 200ks Chandra observations (PI: S. Marchesi) in the first JWST EIGER field centered on the z=6.33 QSO J0100+2802 will allow the candidate to (e) shed light on the source of ionization (AGN vs. star formation) in several z>5 overdensities including a total of 117 systems with spectroscopically confirmed [OIII] emission at z = 5.33 – 6.93.
Overall, the proposed strategy will shed light on the emergence of nuclear accretion activity in the first two billion years of the Universe and will allow us to reach a comprehensive picture of the black hole accretion rate density at z>4.

The PhD candidate will be trained in the selection and characterization of AGN, fully exploiting the wealth of multi-wavelength data currently available. She/he will learn how to handle, analyze, and interpret multi-band data, and will gain expertise in proposal writing and presenting the work at international conferences. Besides, she/he will have the opportunity to collaborate with international research groups, thus gaining invaluable experience for a career in astrophysics.

Contacts: cristian.vignali@unibo.it; fabio.vito@inaf.it; stefano.marchesi@unibo.it.

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Cosmological constraints from the cross-correlation of Gravitational Waves and galaxy catalogs

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Federico Marulli, Andrea Cimatti

Scientific Case: The field of Gravitational Waves (GW) astronomy has been recently exponentially growing. Since the first detection of the electromagnetic counterpart of a GW events thanks to the LIGO and Virgo detection (LIGO Scientific Collaboration et al., 2017), many other events have been discovered. Currently, roughly 90 events have been found, and many more are expected with the improvements of the instruments in the Observing Run 4, and with various GW telescopes planned (Einstein Telescope, Cosmic Explorer). While the standard use of GW as cosmological probes is to use them as standard sirens (see Moresco et al. 2022), recently Mukherjee et al. (2020, 2021) proposed an alternative method that does not rely on directly identifying a redshift counterpart of the GW event. They show that studying the cross-correlation of GW sources with galaxies allows us to break degeneracies in the determination of the distance and redshift of the source, and infer the expansion history from redshift unknown gravitational wave sources. This method is really promising, since it provides a complementary use of GW sources that can be explored in view of the various incoming and planned GW facilities and galaxy surveys.

Outline of the Project: Following Mukherjee et al. (2020, 2021), the aim of this Ph.D. Thesis will be to develop a framework for the combined analysis of GW and galaxy catalog to extract constraints on the cosmological parameters and on the expansion history of the Universe. The project will be developed with the following steps: (i) get familiar with the basics and codes for GW cosmological analyses, to reproduce the constraints on cosmological parameters from standard sirens, (ii) get familiar with the clustering libraries, testing, validating, and optimizing for the case of GW-galaxies the crosscorrelation module in the CosmoBolognaLib libraries, (iii) collect all the available data for GWs and galaxies surveys available (both real data and simulations) to build a library of catalogs for the project, (iv) apply the method to real and simulated data to extract constraints on cosmological parameters with current data and provide forecasts for future surveys (with a particular focus on the synergies between the ESA mission Euclid and future GW facilities such as Einstein Telescope), (v) extend the formalism with a Machine Learning approach as an alternative technique, comparing its results with the standard approaches both in terms of accuracy, feasibility, and performances. The work will be based on the large knowledge of our group of galaxy clustering, starting from the developed libraries CosmoBolognaLib (Marulli, Veropalumbo, Moresco, 2016). In this work, both real and simulated data will be analyzed, taking advantage of the deep involvement of the DIFA cosmology group in the Euclid mission. The Ph.D. student will approach and strengthen knowledges in both galaxy clustering and gravitational waves cosmology and will be also introduced in Italian and international collaborations that study GW (such as Einstein Telescope) and exploit data resulting from the multiwavelenght EM follow-ups of GW events (such as GRAWITA and ENGRAVE).

Contacts:

prof. Michele Ennio Maria Moresco
Associate professor
Department of Physics and Astronomy – University of Bologna
address: via Gobetti, 93/2, 40129, Bologna
email: michele.moresco@unibo.it - phone: 051/2095775